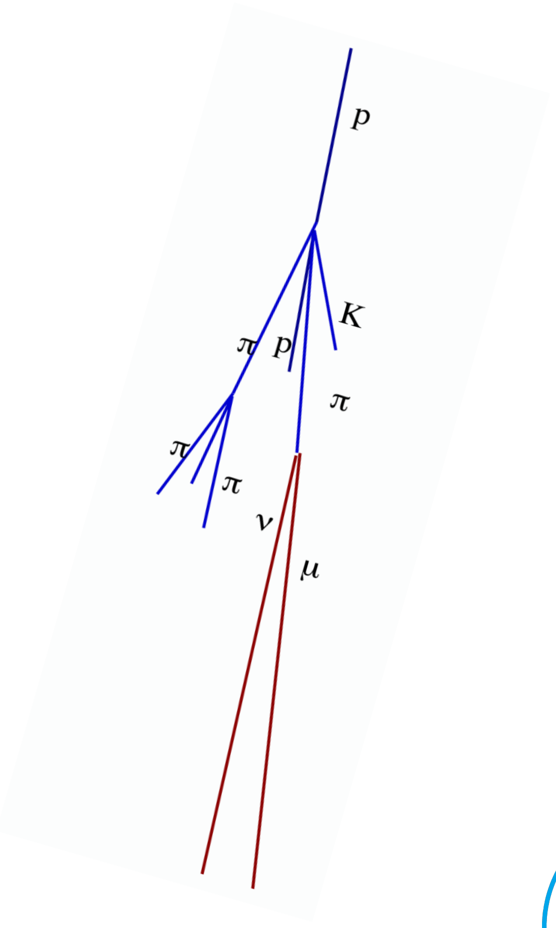
High-energy atmospheric neutrinos

Seminar at Chiba University, Japan, 28th July 2017

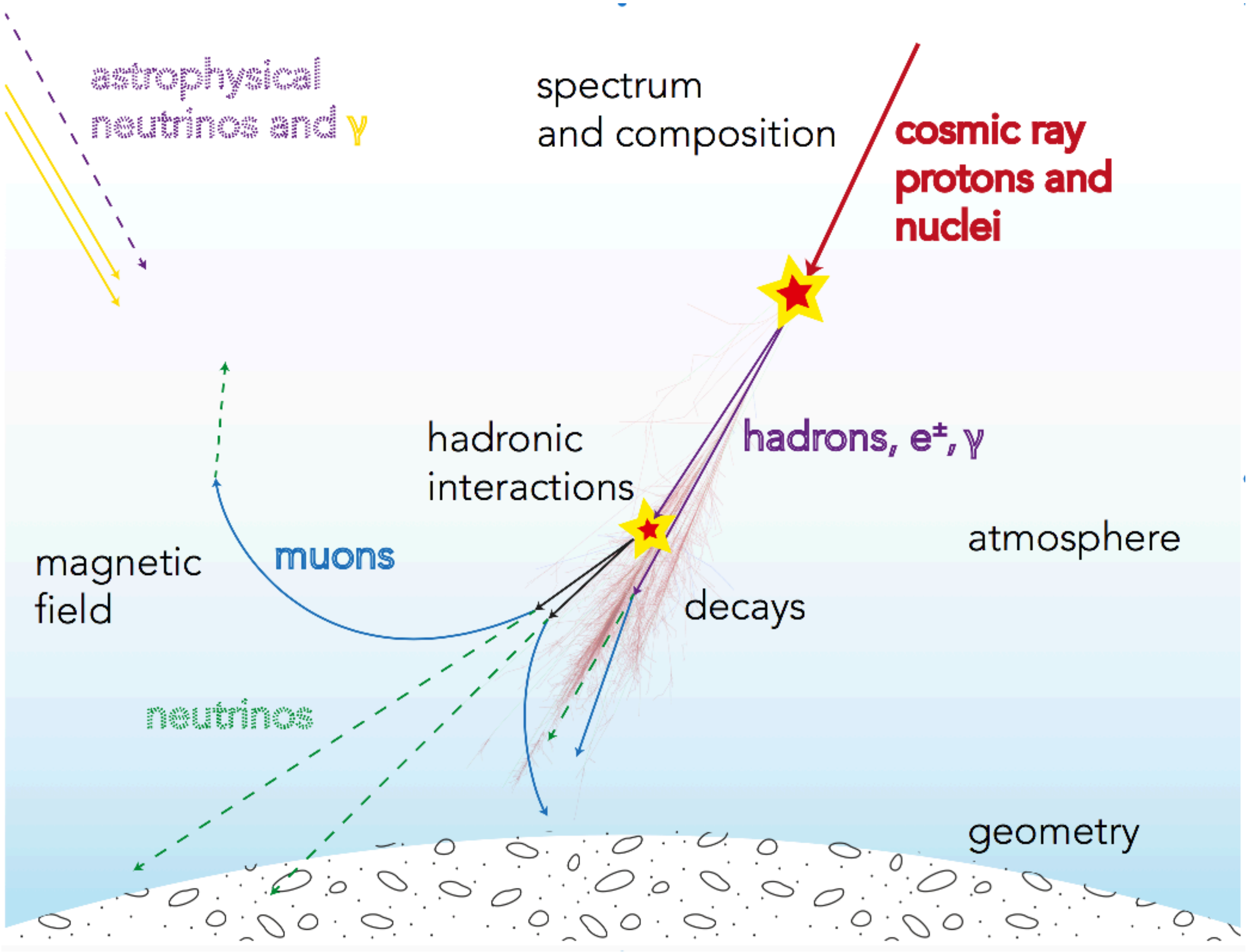


Anatoli Fedynitch
DESY Zeuthen

HELMHOLTZ ASSOCIATION

DESY

Atmospheric leptons



- For high precision calculations all phenomena need accurate modeling

- Not so well known “ingredients”:
  - Cosmic ray spectrum and composition
  - Hadronic interactions
  - Atmosphere (dynamic, depends on use case)
  - (Rare) decays (solved)

- Energy range MeV – EeV!

Production channels

conventional

$$p, A + \mathrm{air} \rightarrow \pi^{\pm}, \pi^{0}, \mathrm{K}^{\pm}, \mathrm{K}^{0}_{\mathrm{S,L}}$$

muons and muon neutrinos

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$

electron neutrinos

$$K^{\pm}, K^{0}_{L} \rightarrow [\pi^{\pm}, \pi^{0}]e^{\pm}\nu_{e}(\bar{\nu}_{e})$$

prompt

$$p, A + \mathrm{air} \rightarrow \mathrm{D}, \Lambda_{\mathrm{C}} \rightarrow \nu_{\mu}, \nu_{\mathrm{e}}, \mu$$

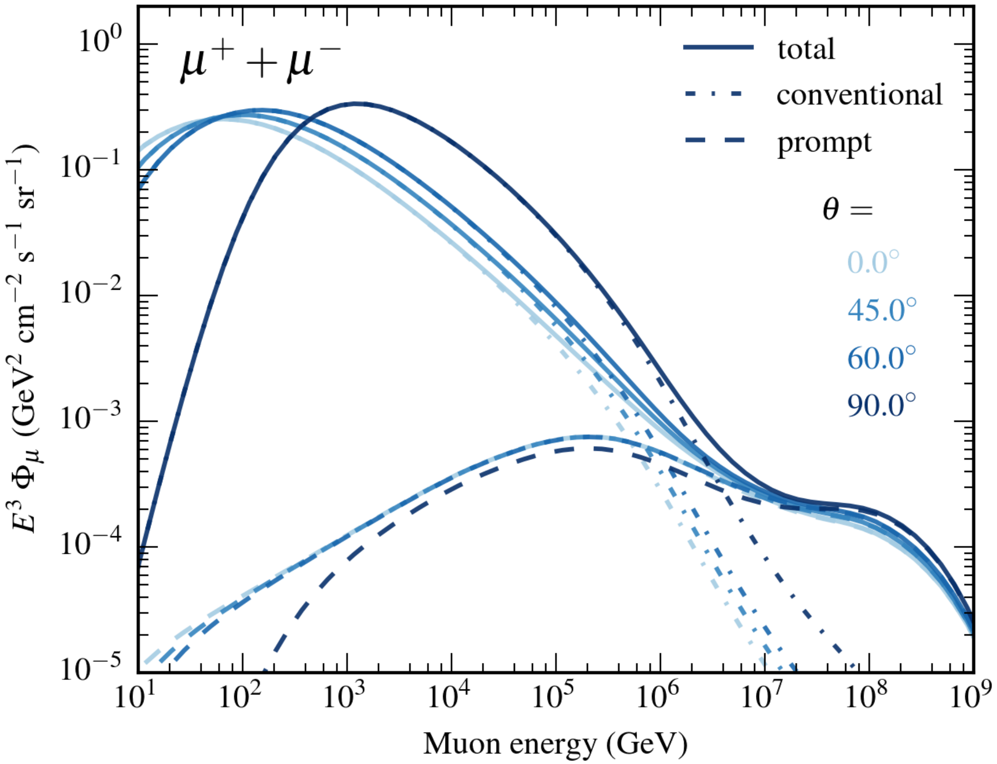
Subset of dominant decay channels

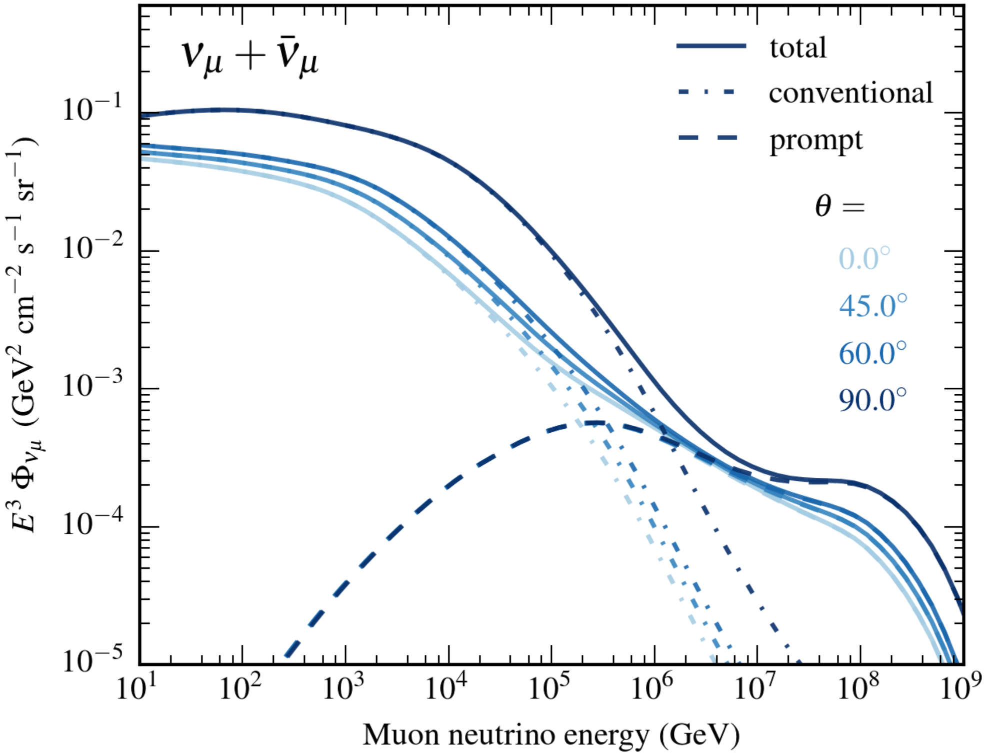
decay channel	branching ratio (BR)
$\mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu}$	100 %
$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$	99.9877 %
$K^{0}_{e3} : K^{0}_{L} \rightarrow \pi^{\pm}e^{\mp}\nu_{e}$	40.55 %
$K^{0}_{\mu 3} : K^{0}_{L} \rightarrow \pi^{\pm}\mu^{\mp}\nu_{\mu}$	27.04 %
$K^{+} \rightarrow \mu^{+}\nu_{\mu}$	63.55 %
$K^{+}_{e3} : K^{+} \rightarrow \pi^{0}e^{+}\nu_{e}$	5.07 %
$K^{+}_{\mu 3} : K^{+} \rightarrow \pi^{0}\mu^{+}\nu_{\mu}$	3.353 %
$D^{+} \rightarrow \overline{K}^{0}\mu^{+}\nu_{\mu}$	9.2 %
$D^{0} \rightarrow K^{-}\mu^{+}\nu_{\mu}$	3.3 %

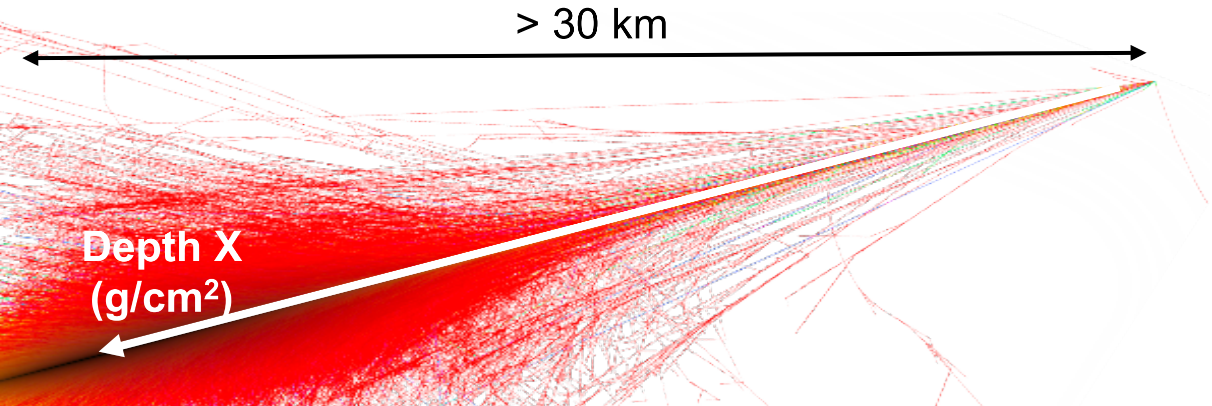
+ charge conjugates

http://pdg.lbl.gov

General shape of high energy lepton spectra







Zenith angle changes competition between decay and (re-)interaction

Transport equations (hadronic cascade equations)

System of non-linear PDE for each particle species *h* (~62 x #E-bins) *:*

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} - \frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)}$$

Interactions with air

Decays

Energy losses (radiative)

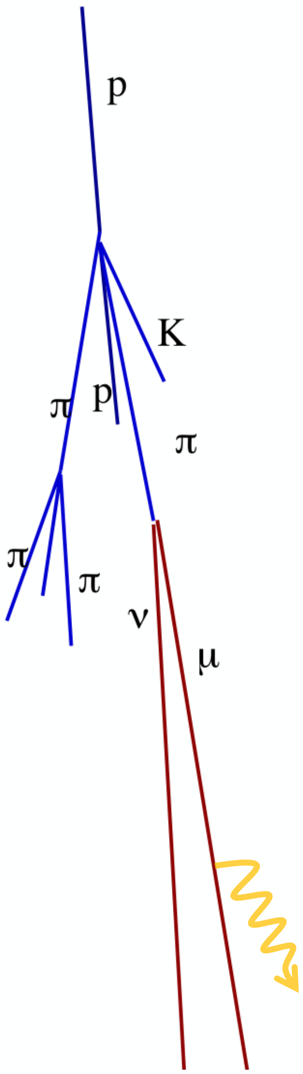
Re-injection from interactions

Re-injection from decays

cosmic ray physics

atmospheric physics

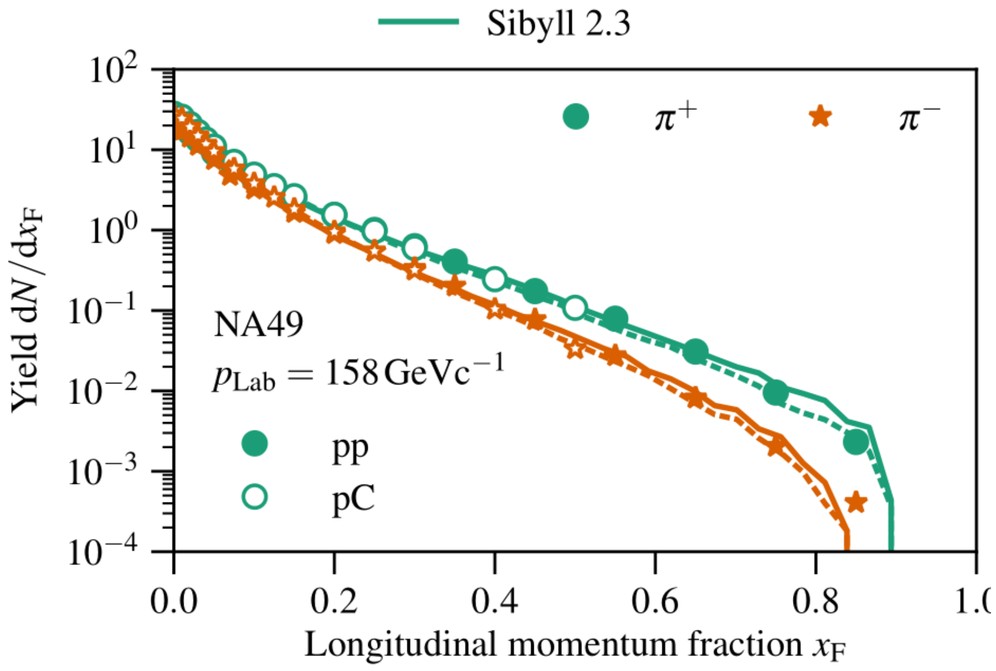
particle physics

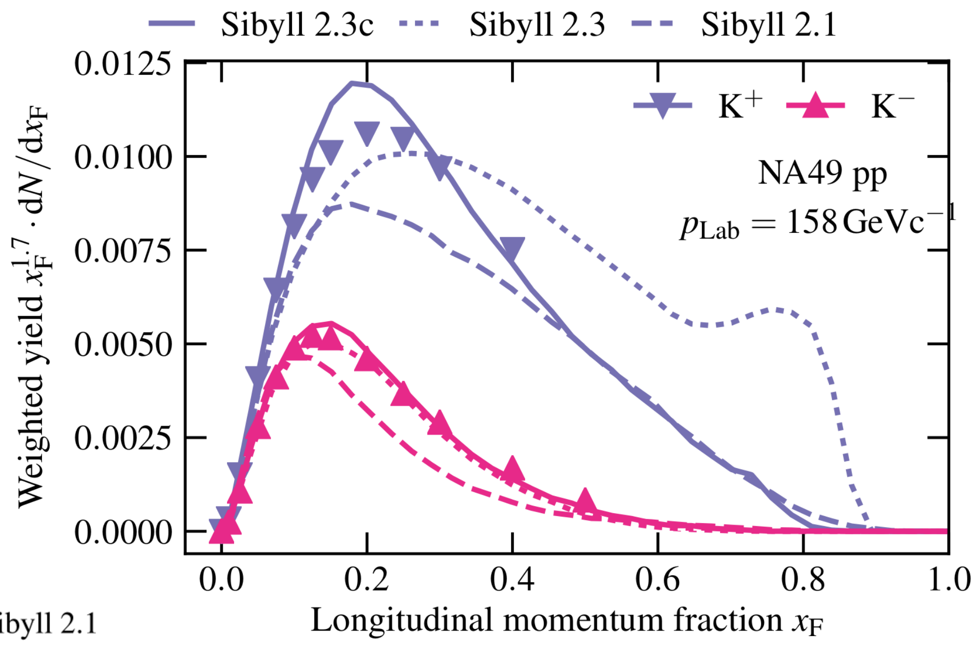


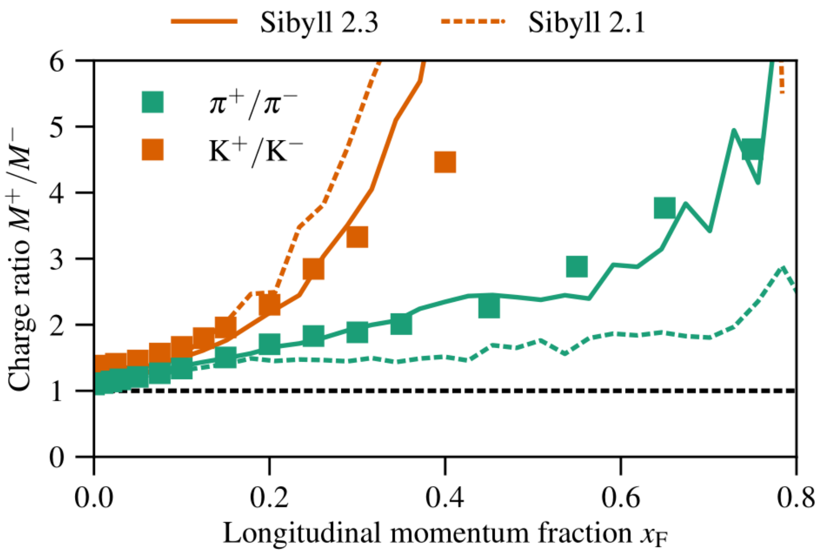
DESY

Inclusive secondary particle distributions (as in fixed-target experiment)

Measurements at low energy, no clear extrapolation recipe





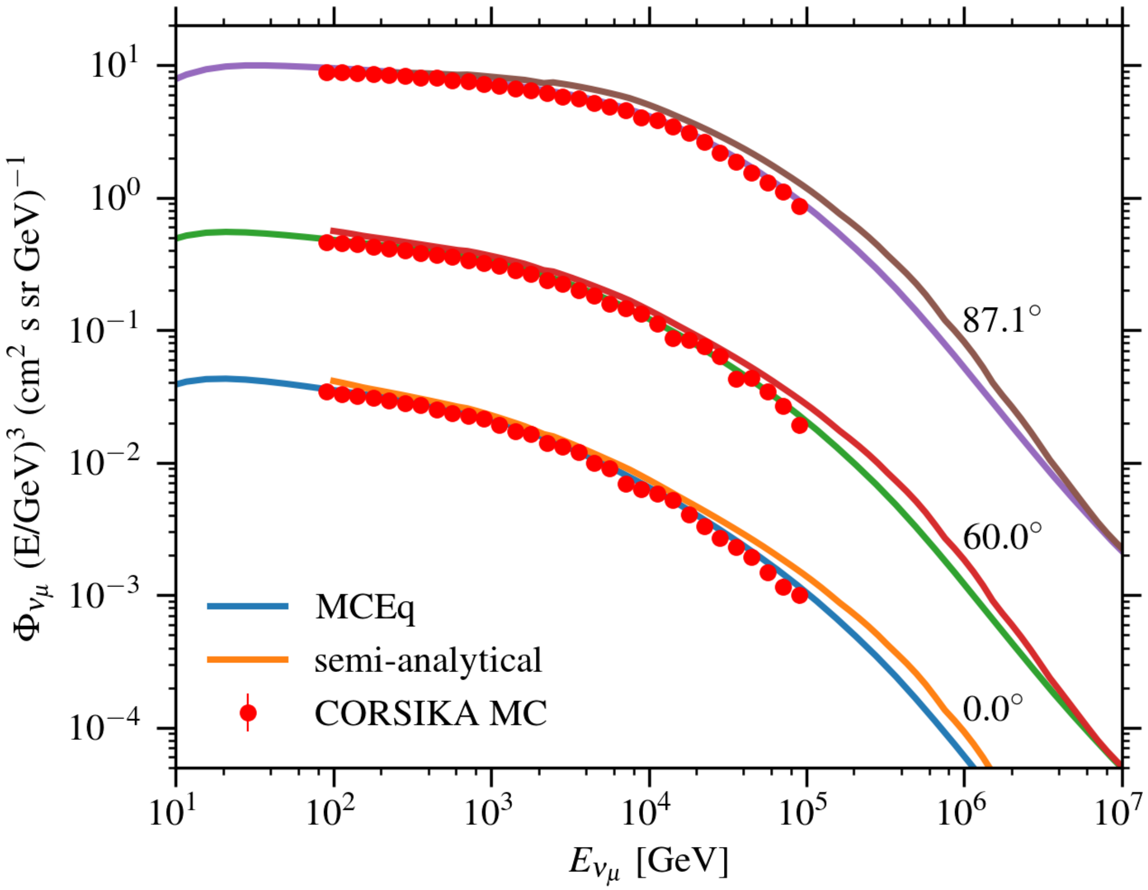


No kaon data for proton-carbon!

F. Riehn, R. Engel, A. Fedynitch, T. K. Gaisser and T. Stanev. arXiv:1510.00568, PoS ICRC 2015, 1129 (2015)

SIBYLL 2.3c: Riehn et al. PoS(ICRC2017)301

MCEq: open-source Python code

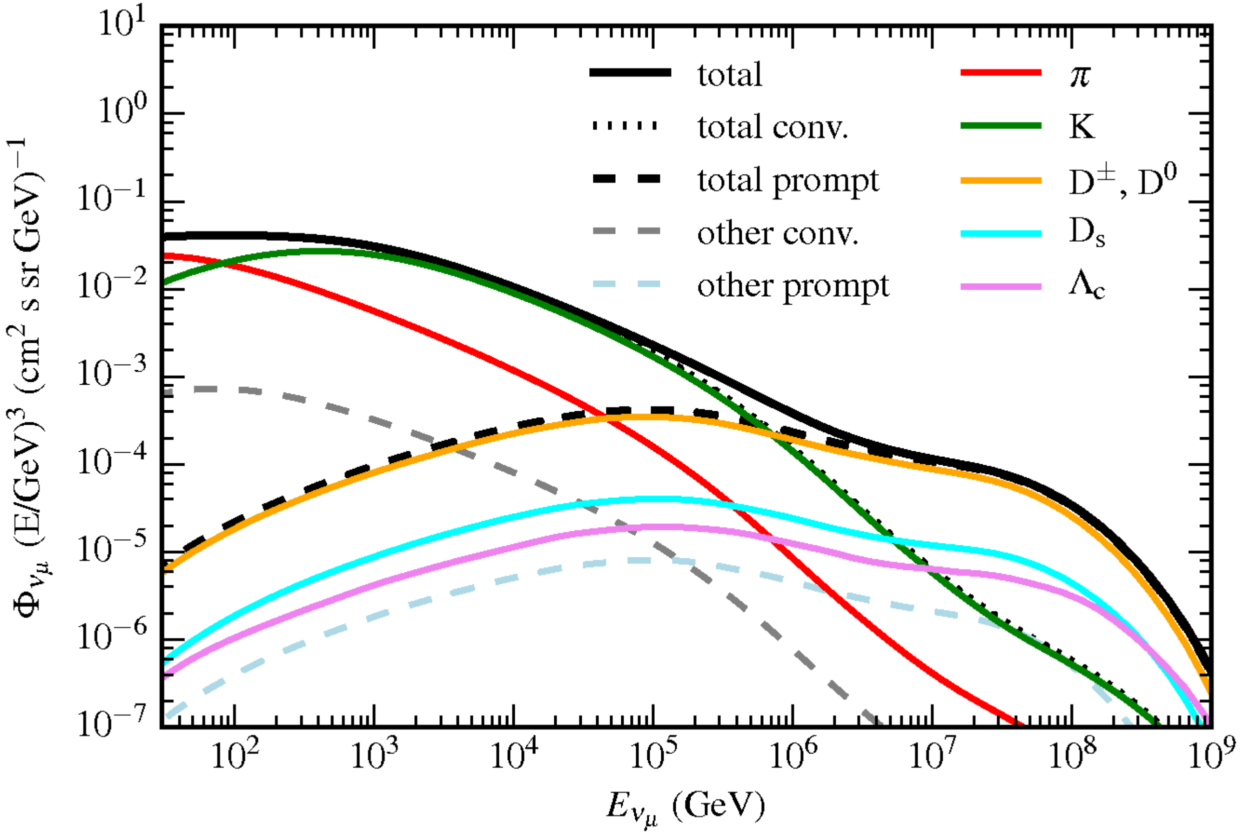


- Simultaneous solution of up to 8000 kinetic equations
- Energy range 1 (30) GeV – 10^{11} GeV
- All models included
- High optimization: multi-core, GPU, … (BLAS, MKL, CUDA) (~milli-seconds!)
- MIT licensed @ https://github.com/afedynitch/MCEq

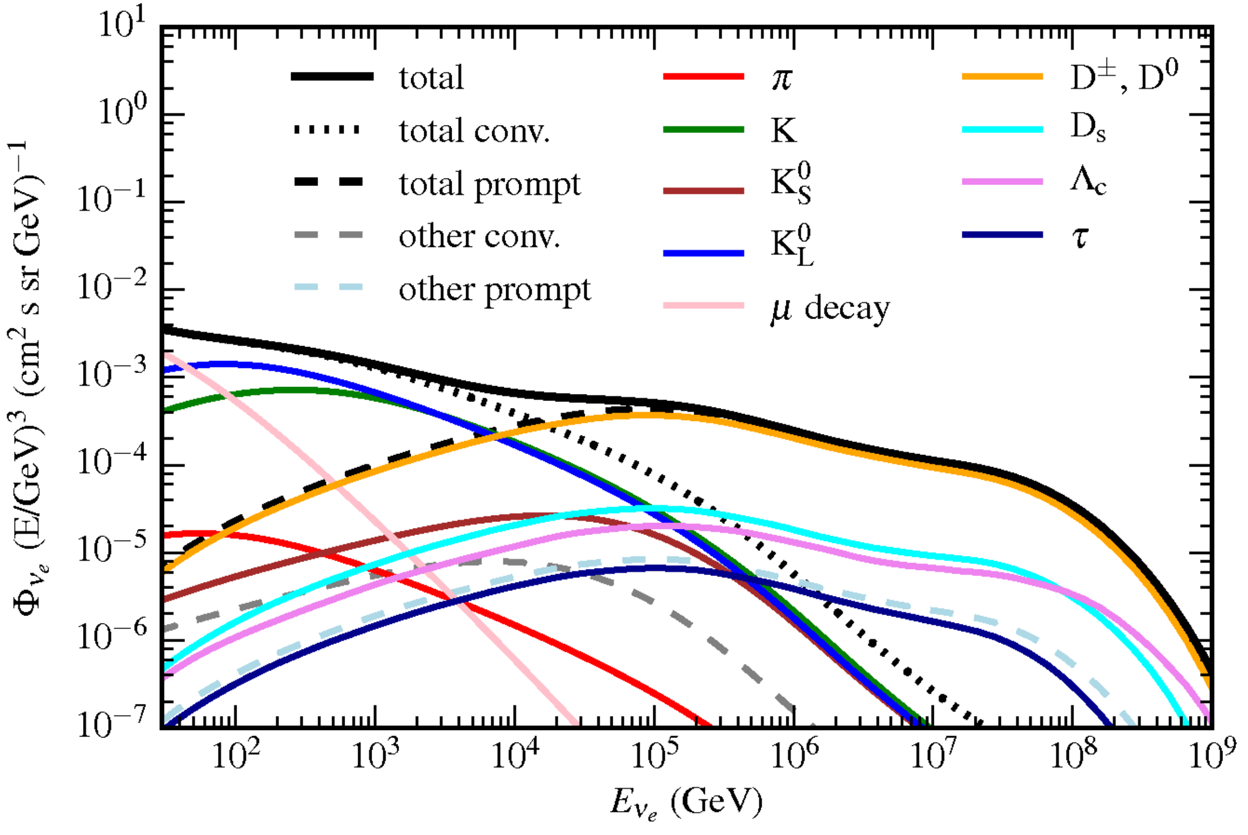
CORSIKA: A. Fedynitch, J. Becker Tjus and P. Desiati, PRD 2012
MCEq: A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor. PoS ICRC 2015, 1129

Relevant hadrons for neutrino production

Muon neutrinos



Electron neutrinos

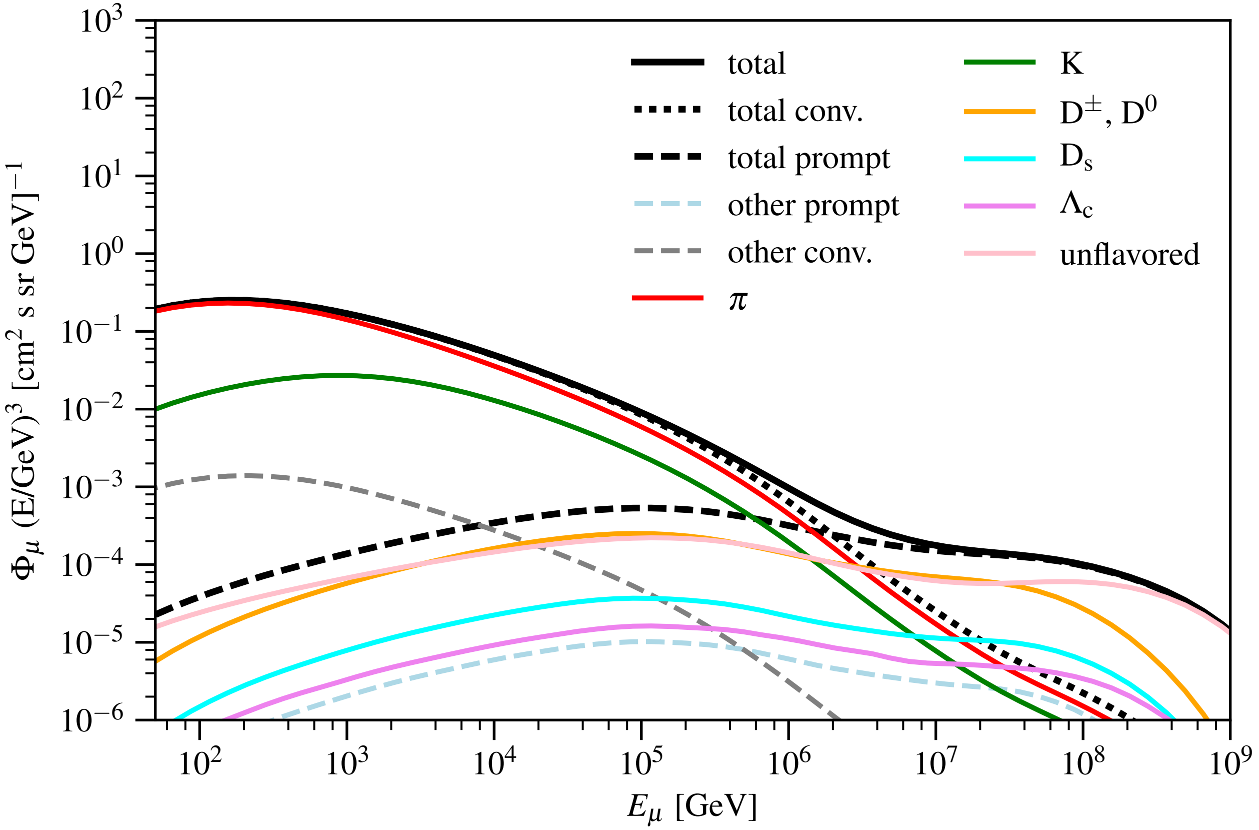


pion decay kaon decay charm decay

muon decay kaon decay charm decay

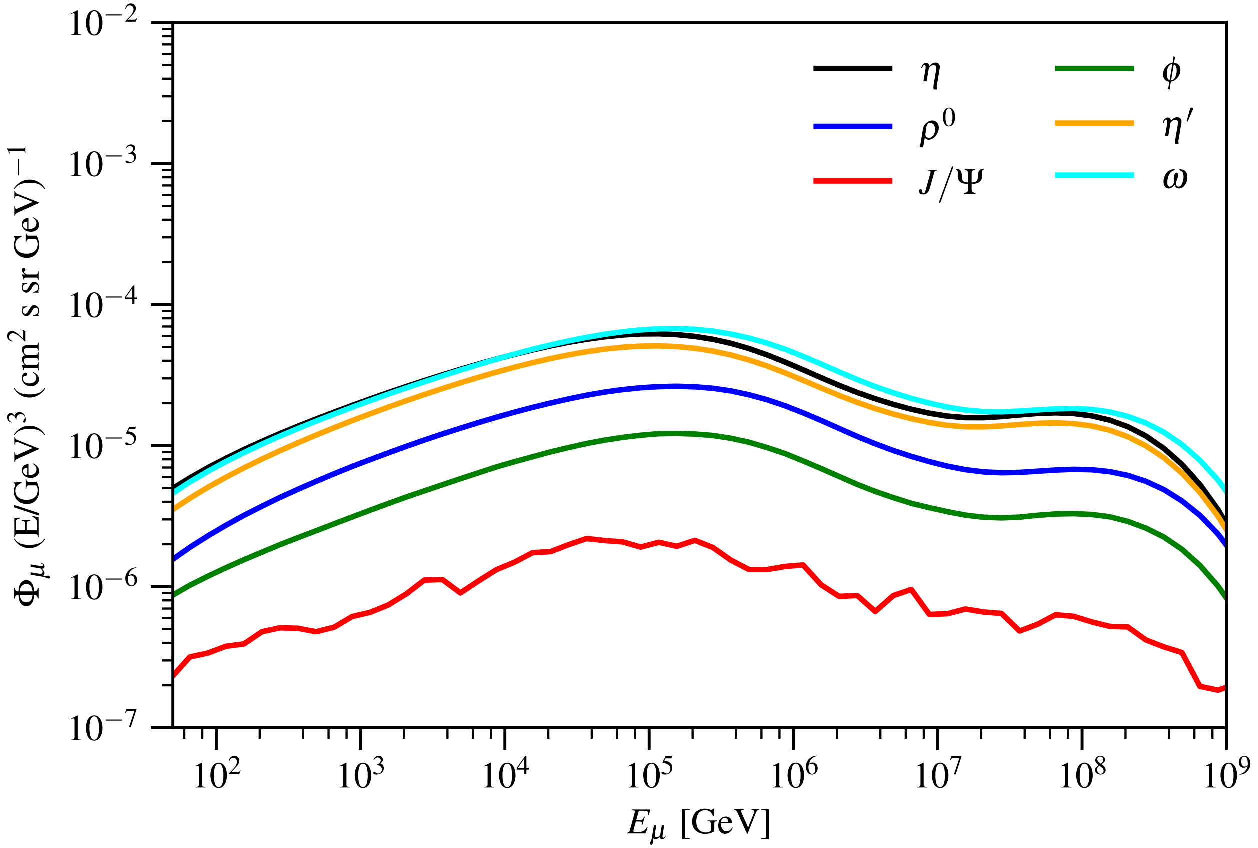
Relevant particles for muon production

Muons



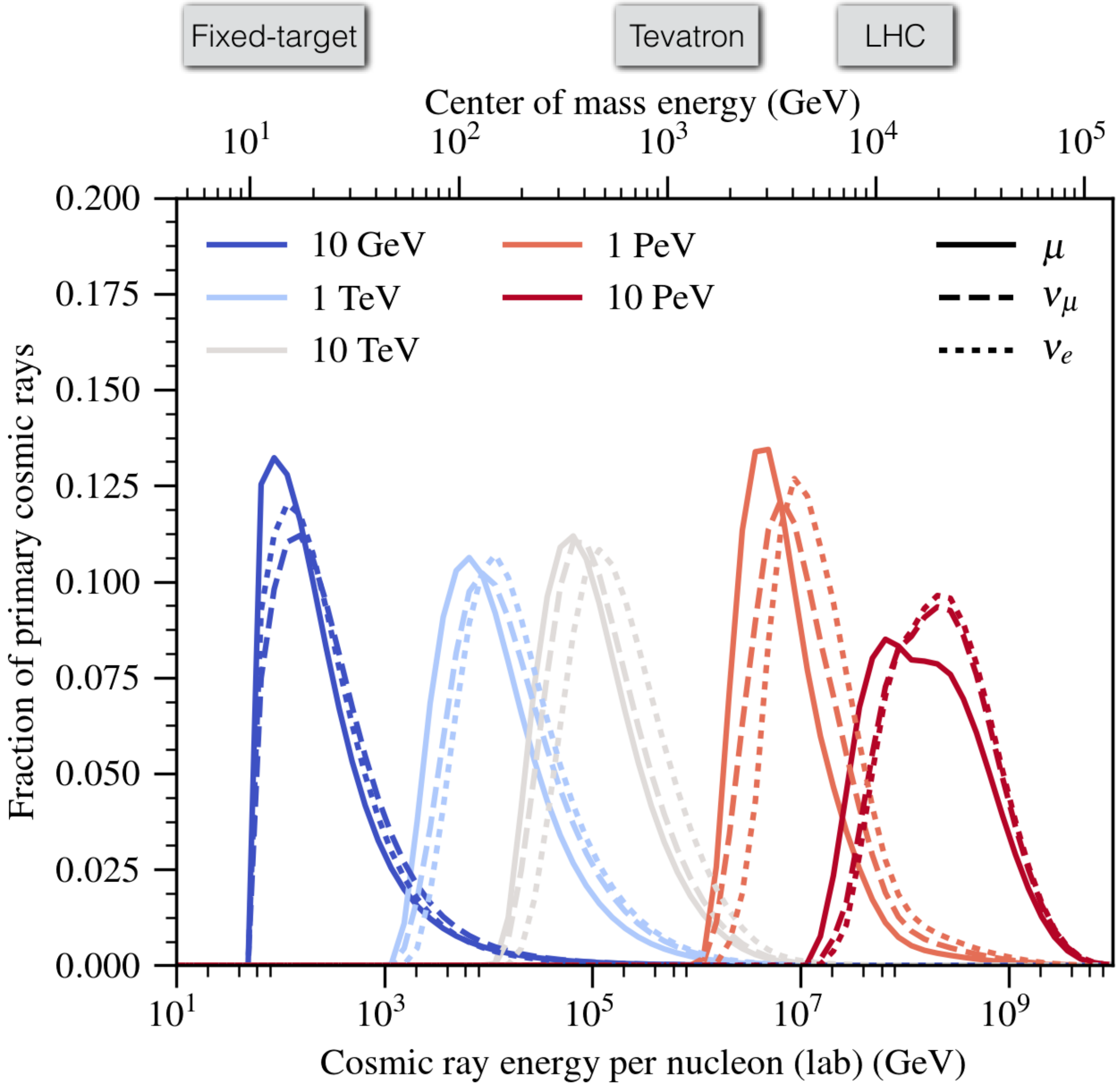
pions + kaons charm + unflv. unflavored

..from unflavored mesons



These mesons decay into muon pairs with small branching ratios

Relation between lepton and cosmic ray energy



Energy range covered by particle accelerators.

If energy is not a problem…

Kinematic variables

$$\theta = \arctan \frac{p_T}{p_z}$$

$$\eta = -\ln\left(\tan \frac{\theta}{2}\right)$$

$$x_{\mathrm{lab}} = \frac{E_{\mathrm{secondary}}}{E_{\mathrm{primary}}} \approx \frac{p_{z,\mathrm{secondary}}}{E_{\mathrm{primary}}}$$

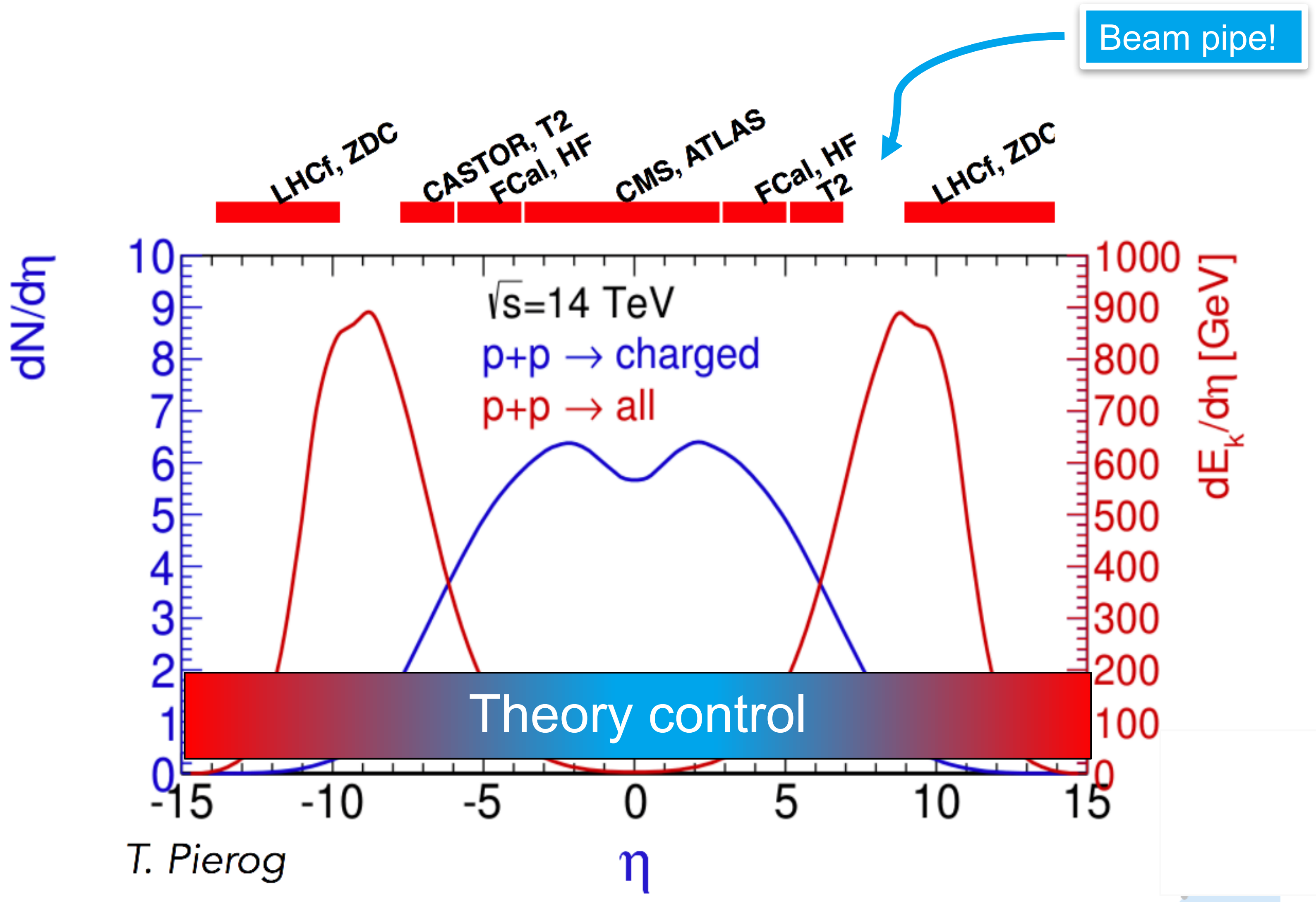
For atmospheric leptons

$$p_z \sim \mathrm{TeV} - \mathrm{PeV}$$

$$p_T \sim \text{few GeV}$$

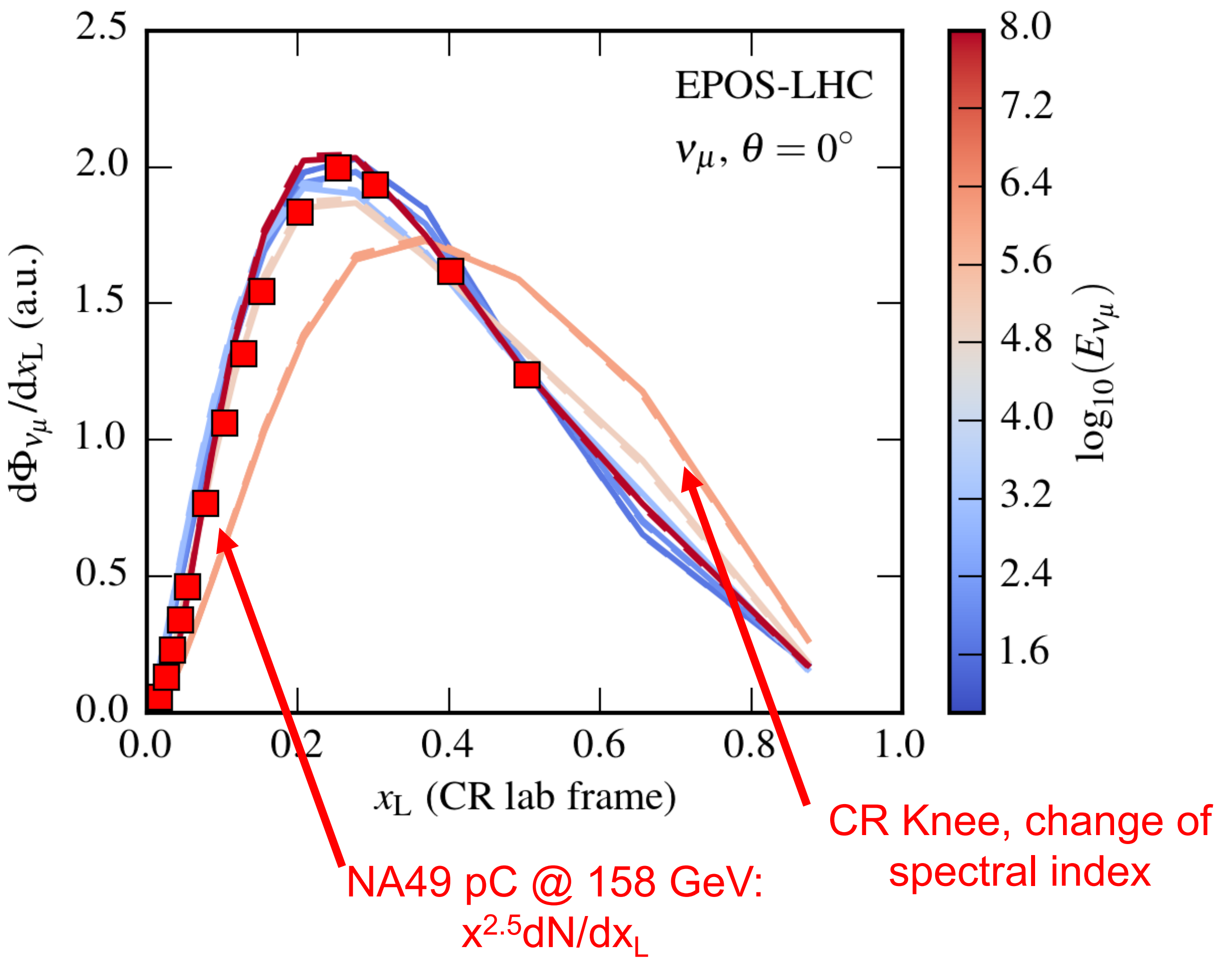
$$\theta \sim \mu\mathrm{rad}$$

$$x_{\mathrm{lab}} > 0.1, \quad \eta \to \infty$$



Secondary hadron (pion/kaon/charm) energy fractions

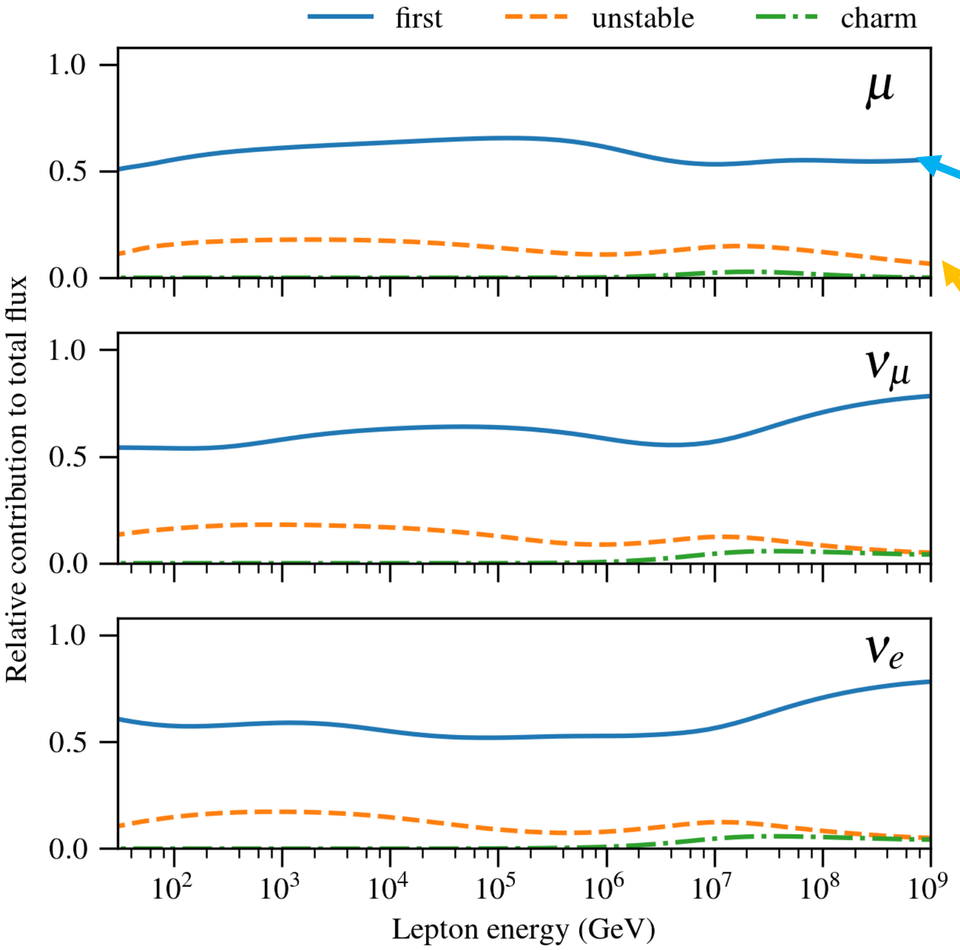
x_{lab} regions contributing to inclusive muon neutrino flux

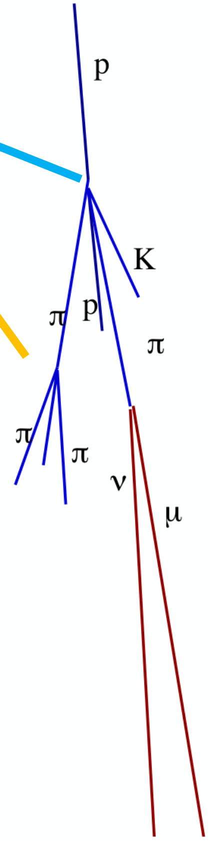


- Atmospheric leptons are sensitive mostly to x_{lab} ~ 0.2 and above
- Reason: steepness of primary CR spectrum

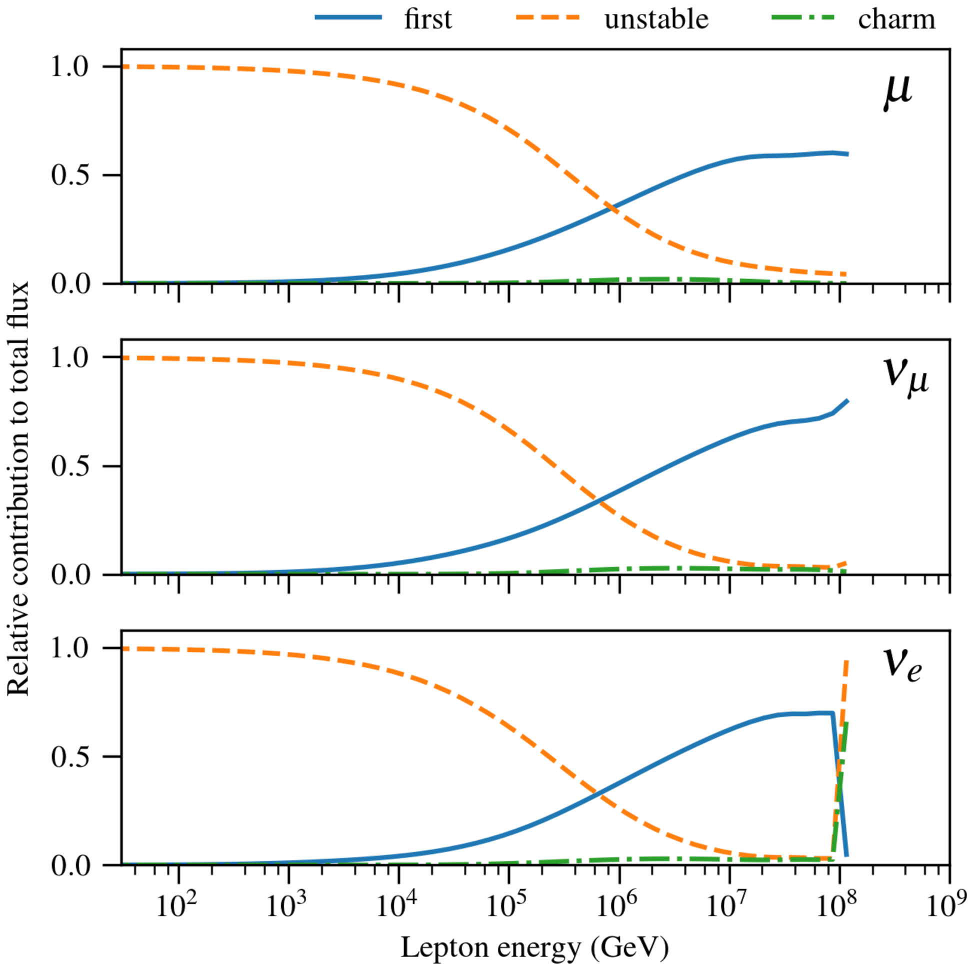
Role of secondary interactions in cascade

Inclusive leptons



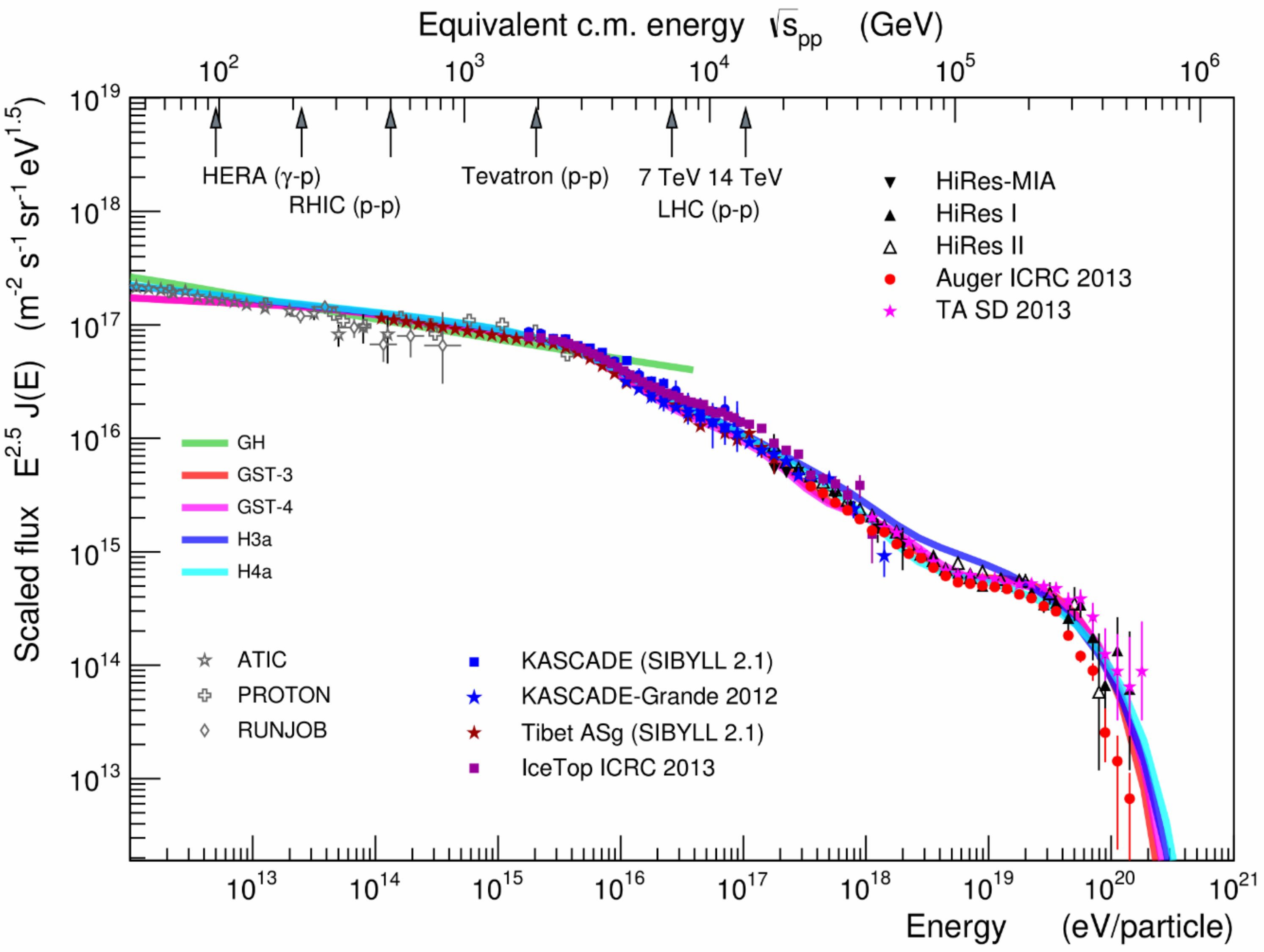


100 PeV p air shower



It's not 90% from first interaction (as often assumed)

Comic ray spectrum at the top of the atmosphere

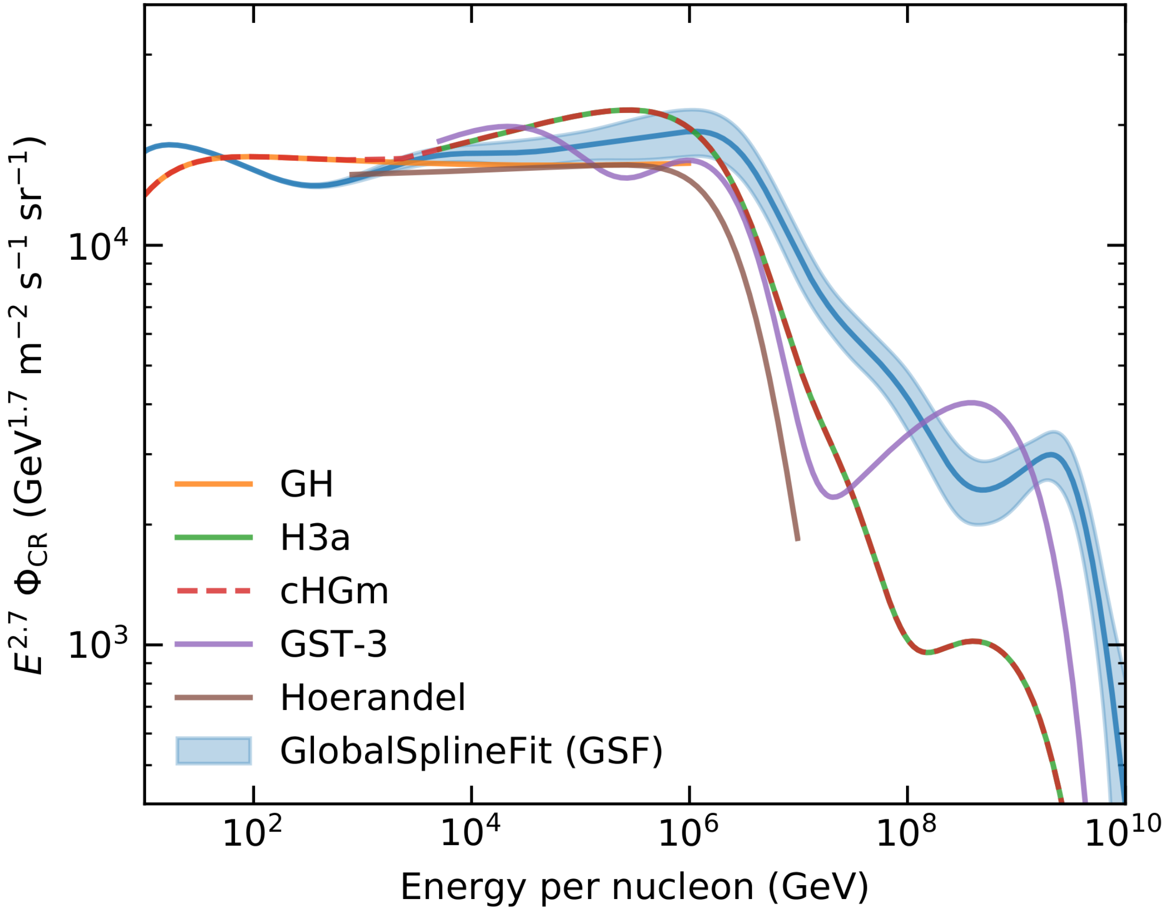


- None of the shown models is a real fit (with errors and covariance matrix)
- GST-X and HXa are quite extreme assumptions for UHECR
- No error estimates!

HXa:
T. K. Gaisser,
Astropart. Phys. 35 (2012) 801–806
GH:
T. K. Gaisser and M. Honda,
Ann. Rev. Nucl. Part. Sci. 52 (2002) 153–199
GST-X:
T. K. Gaisser, T. Stanev, and S. Tilav,
Front. Phys.(Beijing) 8 (2013) 748–758

Update of GH (not shown):
J. Evans, D. Porzio et al., 1612.03219

New GSF all-nucleon flux (input for atm. neutrino calculations)



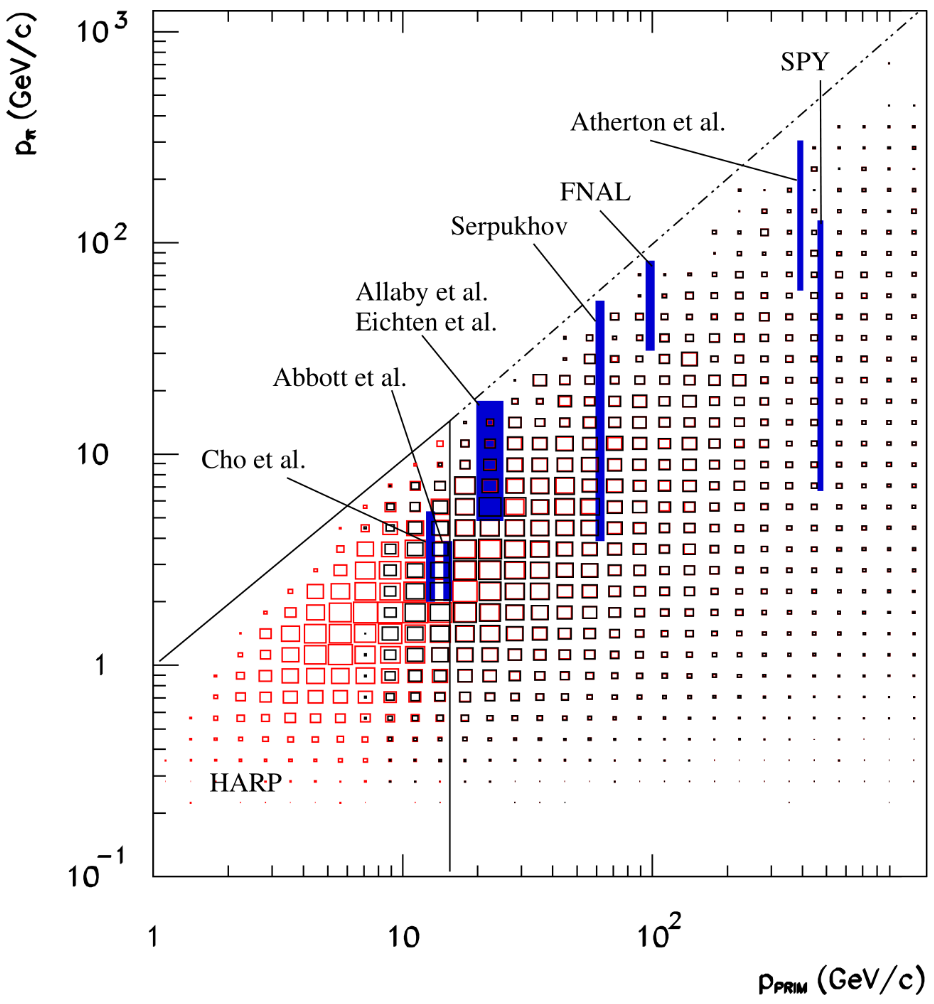
- Novel global fit to entire CR spectrum: *Dembinski et al., PoS(ICRC2017) 533*
- Wavy feature at lower energies are due to the hardening of proton and He spectra
- Increase of error around 10 TeV because of the gap between direct and indirect exp.
- Higher flux at the knee and harder spectral index between knee and ankle
- Latter effect comes from the **lighter composition at the knee** as in other models
- Mainly driven by KASKADE Gr. and latest data from IceTop and TUNKA

Hadronic uncertainties: current state of the art

- "*Uncertainties in atmospheric neutrino fluxes*", G. D. Barr, S. Robbins, T. K. Gaisser, and T. Stanev, Phys. Rev. D 74, 094009 (2006)
- Cut phase-space in regions/slices in E_{lab} and x_{lab} and **assign** uncertainty to each slice (uncorrelated)
- **Draw-back 1**: Uncertainty assigned by hand and judged only from availability of experimental data (not how well TARGET described it)
- **Draw-back 2**: The "central value" is assumed to be TARGET. Scheme doesn't tell anything about "best estimate".

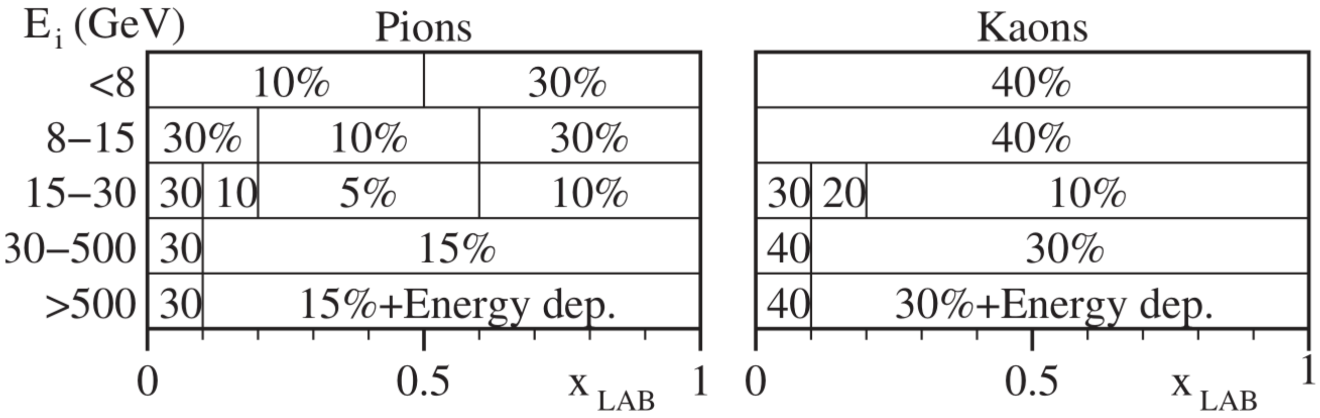
Up to 10 TeV neutrino energy, no muons.

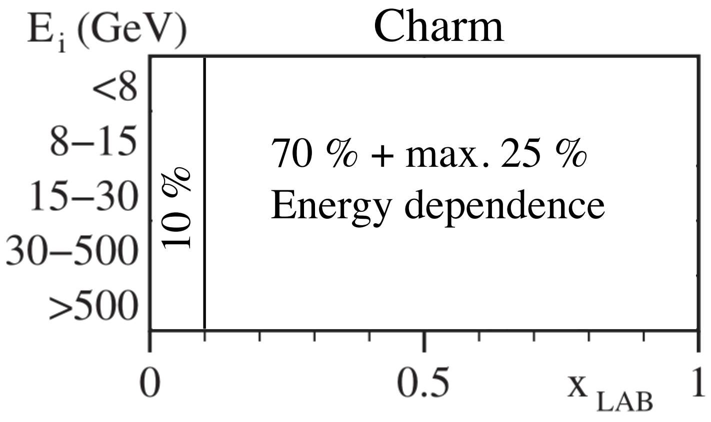
PHYSICAL REVIEW D **74,** 094009 (2006)



Implementation of the “Barr scheme” in MCEq

The regions





- Compute partial derivatives wrt. phase-space regions, i.e. $\frac{\partial \Phi_\nu}{\partial \mathrm{W}}$
- No correlations between phase-space regions (as in Barr et al.) or add. correlations

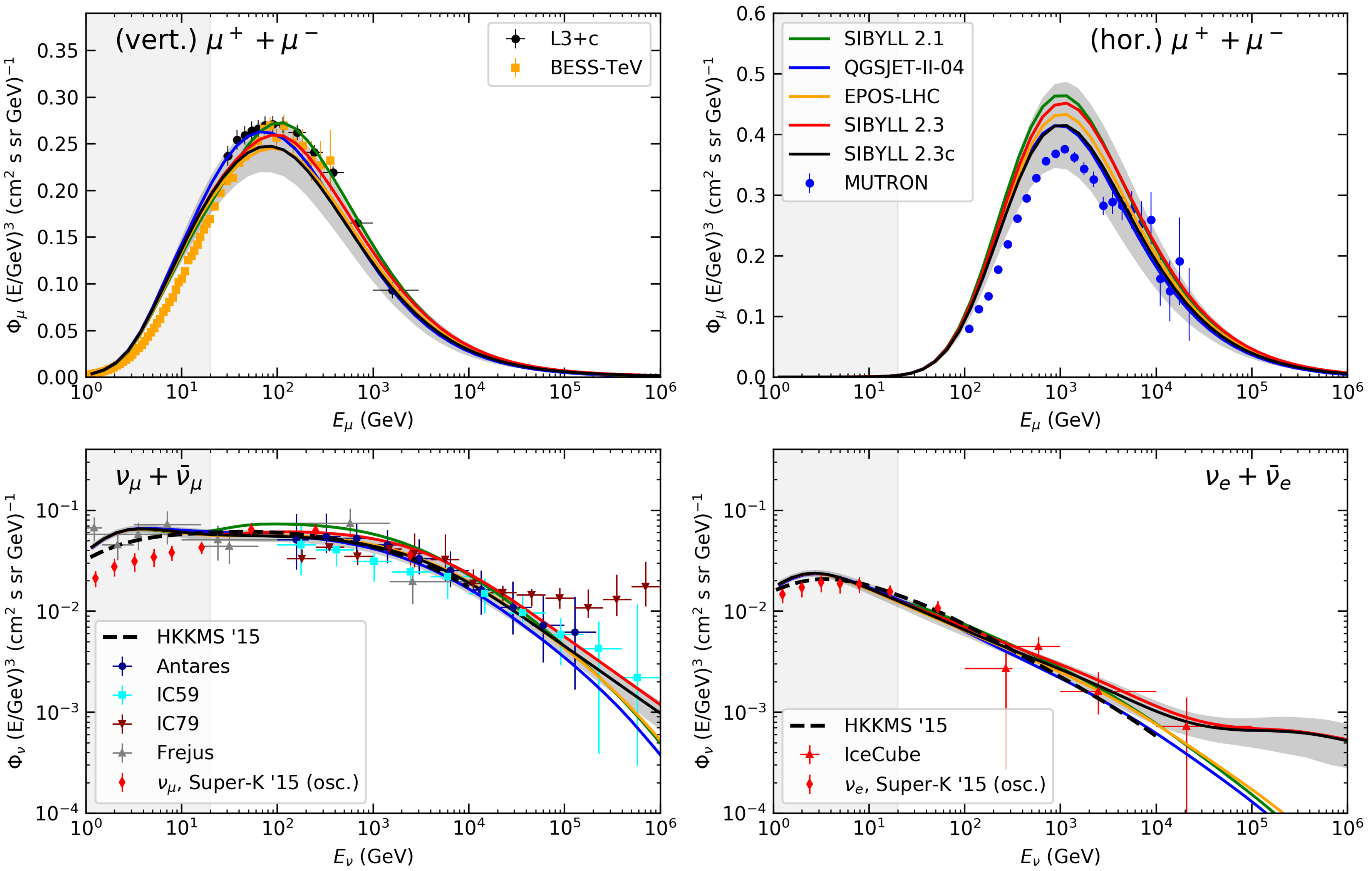
Elements of Jacobian (numerical)

$$J_{E_i j} = \frac{\partial \Phi_\nu(E_i)}{\partial p} = \frac{\Phi_\nu(\delta p_j +) - \Phi_\nu(\delta p_j -)}{2\delta p_j}$$

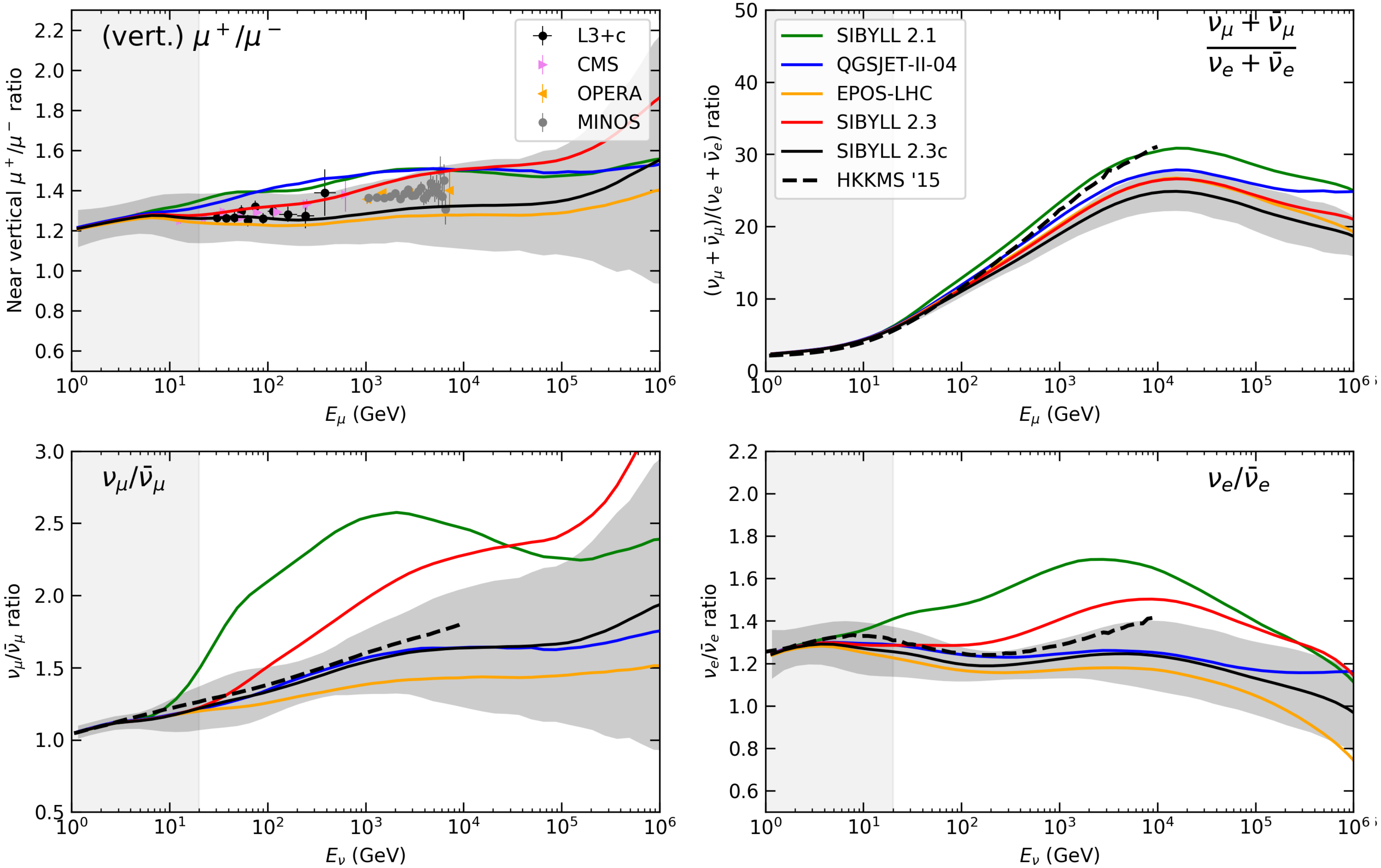
Error propagation

$$\mathrm{cov}[\Phi_\nu(E_i), \Phi_\nu(E_j)] = \sum_{mn} J_{E_i m} J_{E_j n} \mathrm{cov}[p_m, p_l]$$

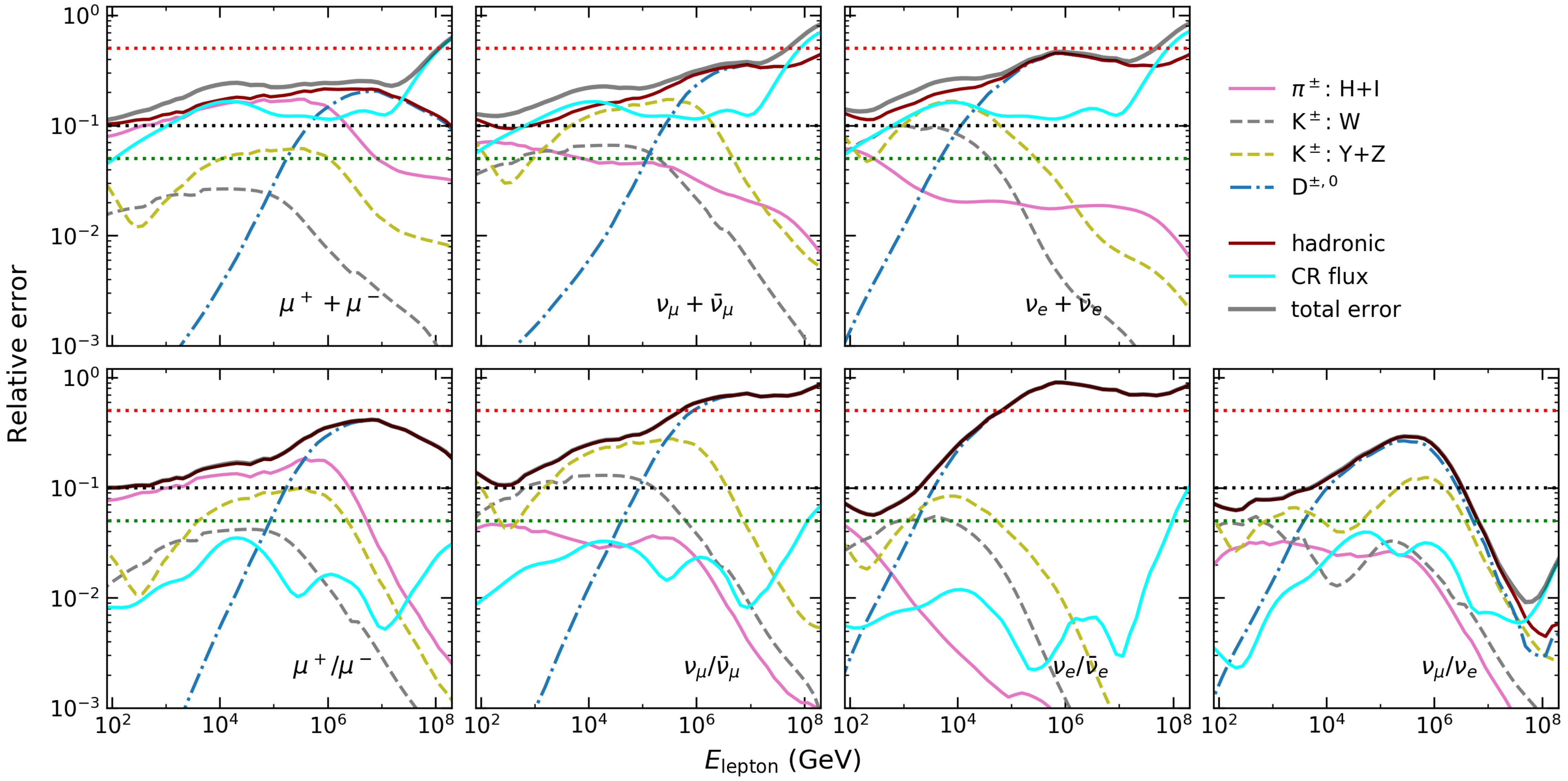
Uncertainties of lepton fluxes



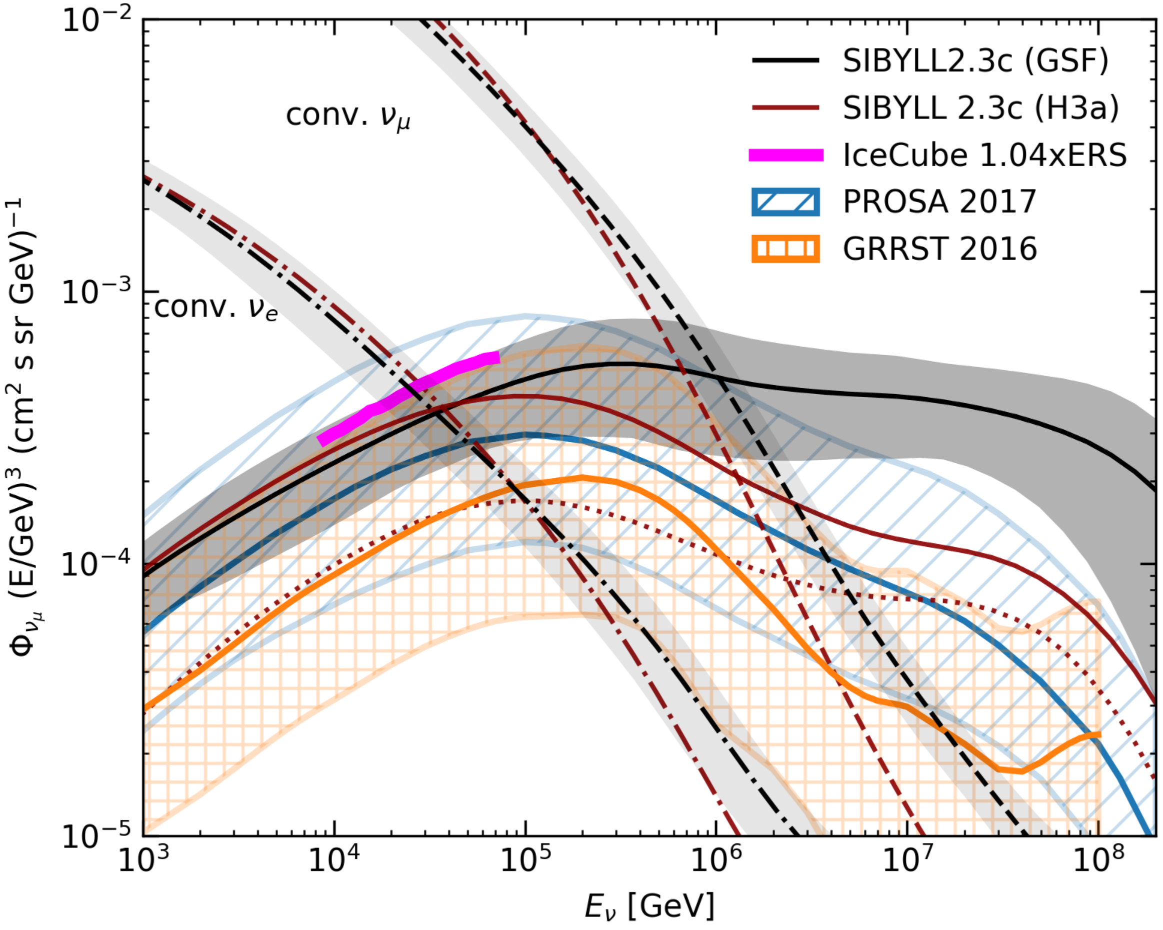
Uncertainties of lepton ratios



Hadronic uncertainties for high energy leptons



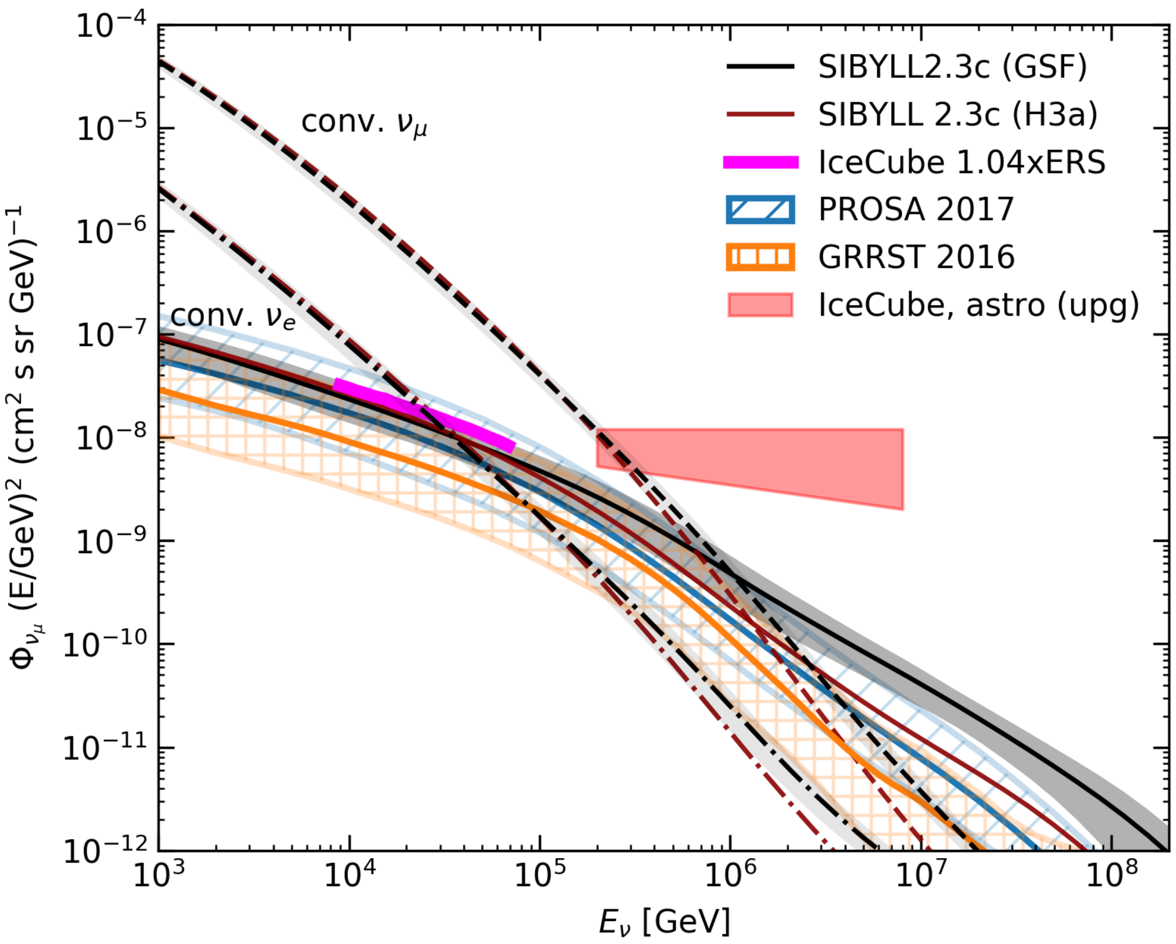
Prompt neutrinos from decays of charmed mesons



- SIBYLL 2.3c is the only full MC model
- Compatible with LHC data and IceCube limit
- New CR flux model (GSF) changes situation a bit
- Uncertainties from QCD very large and calculations are compatible
- Uncertainties from pQCD calculations are presumably overestimated, since LHC measurements of charm are not taken into account

IceCube: Astrophys.J. 833 (2016)
GMS: Garzelli et al., JHEP 1510 (2015) 115
BERSS: Bhattacharya et al. JHEP 2015: 110

Prompt neutrinos from decays of charmed mesons



- SIBYLL 2.3c is the only full MC model
- Compatible with LHC data and IceCube limit
- New CR flux model (GSF) changes situation a bit
- Uncertainties from QCD very large and calculations are compatible
- Uncertainties from pQCD calculations are presumably overestimated, since LHC measurements of charm are not taken into account

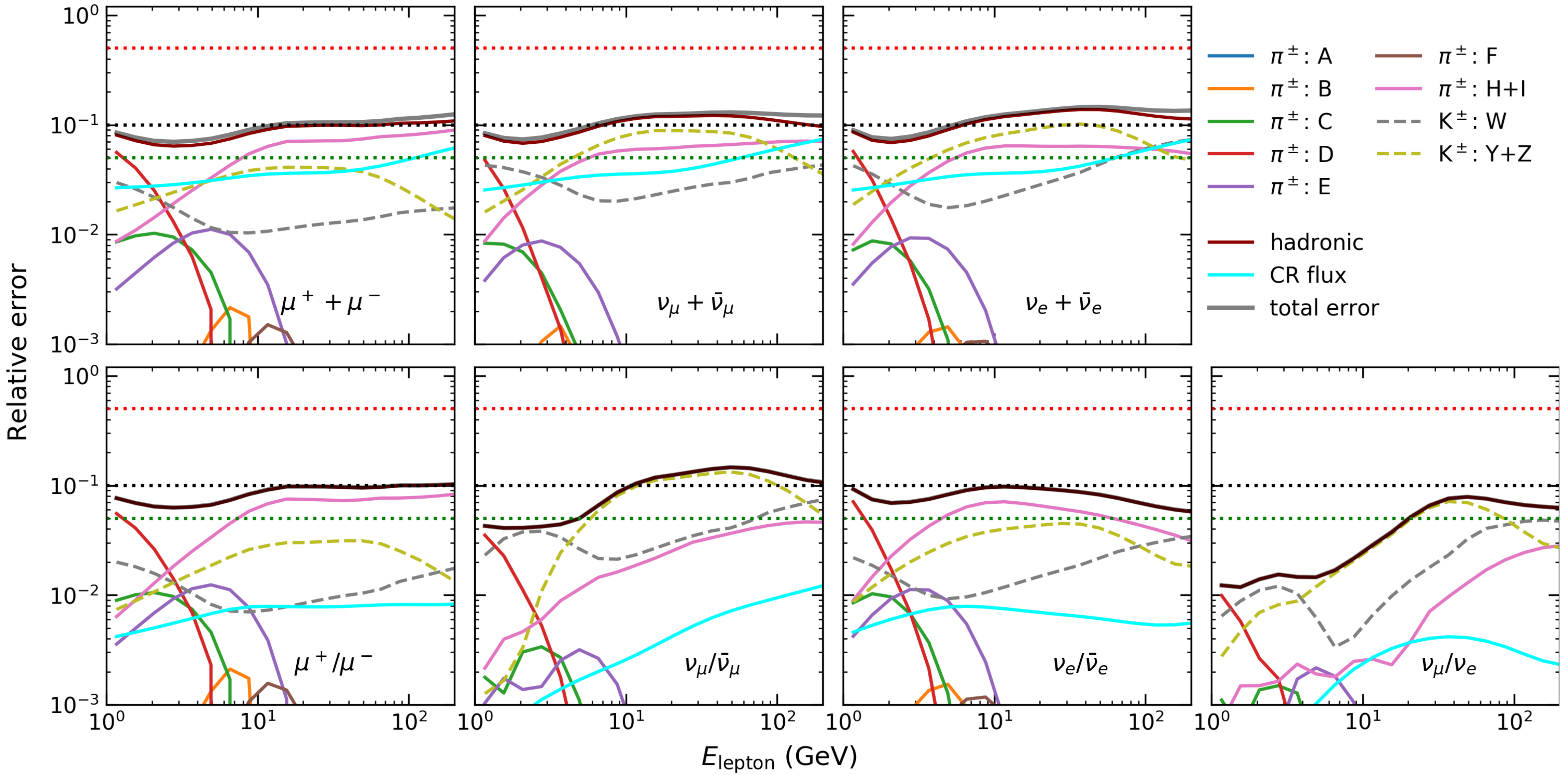
IceCube: Astrophys.J. 833 (2016)
GMS: Garzelli et al., JHEP 1510 (2015) 115
BERSS: Bhattacharya et al. JHEP 2015: 110

Conclusions

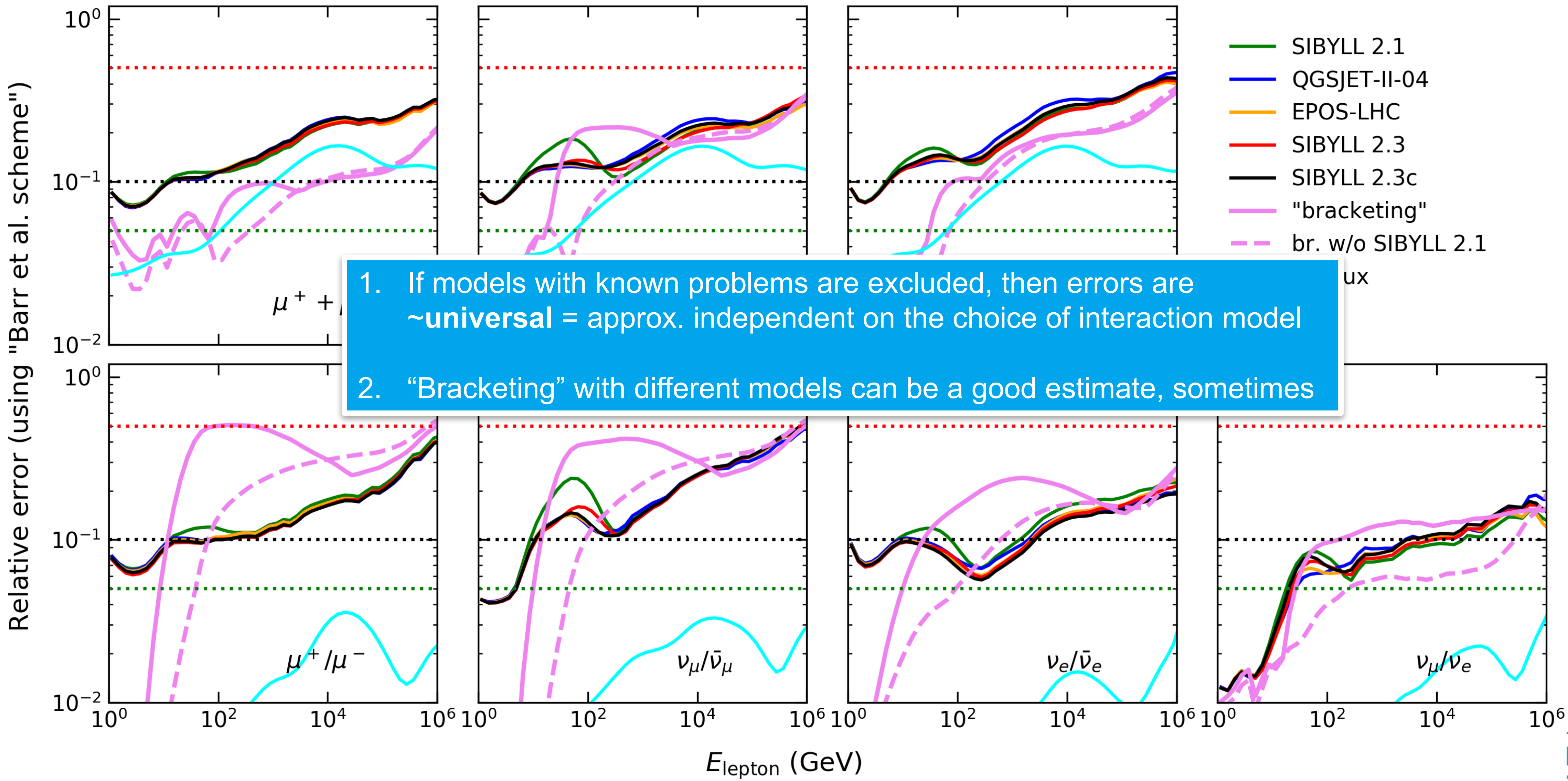
- Relevant cosmic ray energies, contributing particles and their phase-space understood in detail.
- Progress transparent to the community through an open source code, support, etc.
- Cosmic ray uncertainties are quantified to our best knowledge. The numerical model including the covariance matrix will be open source, as well.
- Uncertainties, at the level of Barr et al. can be reproduced with MCEq and corresponding tools will be published, asap.
- High-quality atmospheric muon and neutrino data (incl. systematics, error correlation matrix, etc.) would definitely help

DESY

Hadronic uncertainties below 200 GeV



Hadronic uncertainties computed with different interaction models

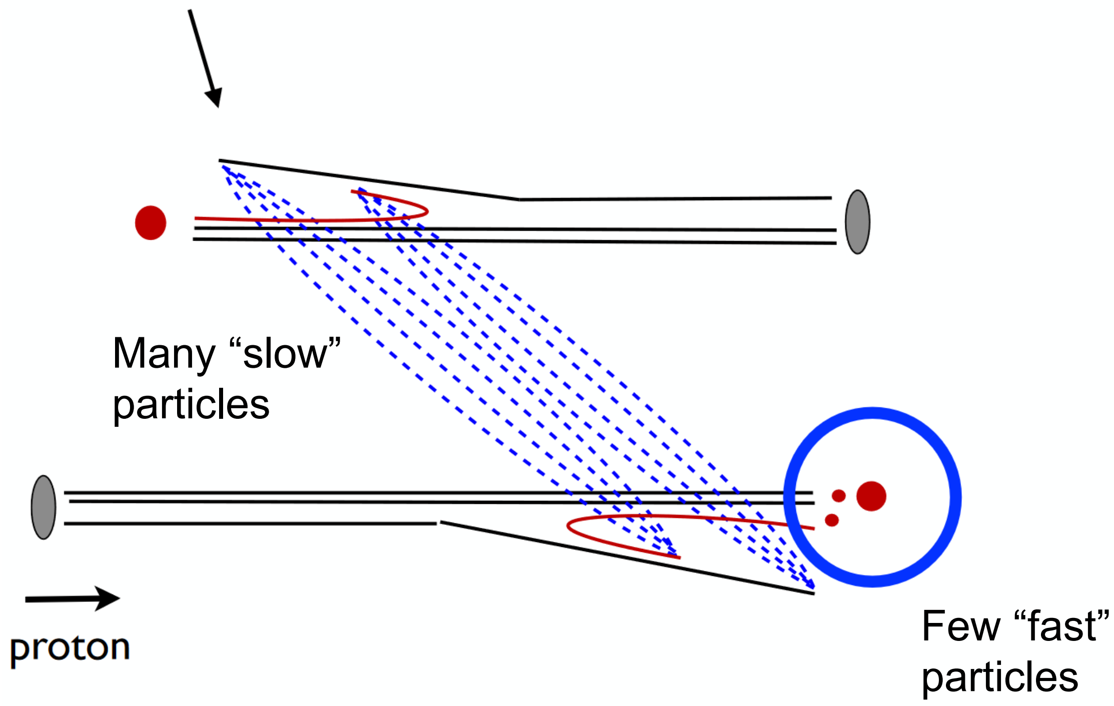


1. If models with known problems are excluded, then errors are **~universal** = approx. independent on the choice of interaction model

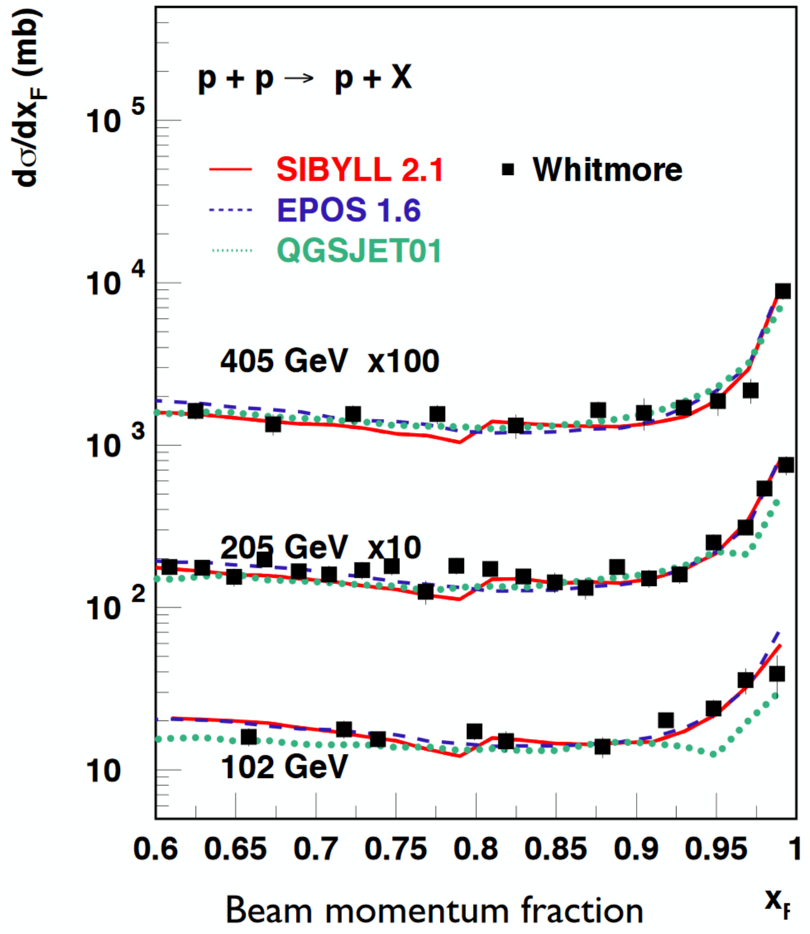
2. "Bracketing" with different models can be a good estimate, sometimes

Leading particles

Model-dependent distributions of momentum given to partons

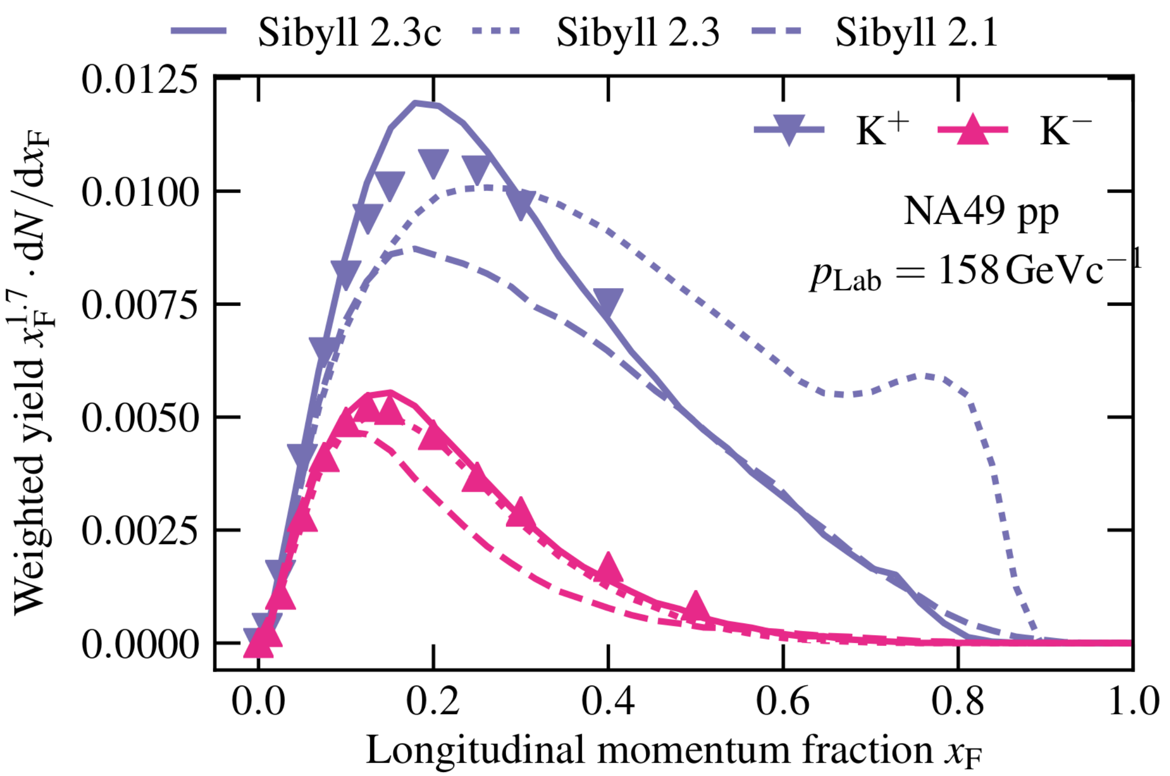


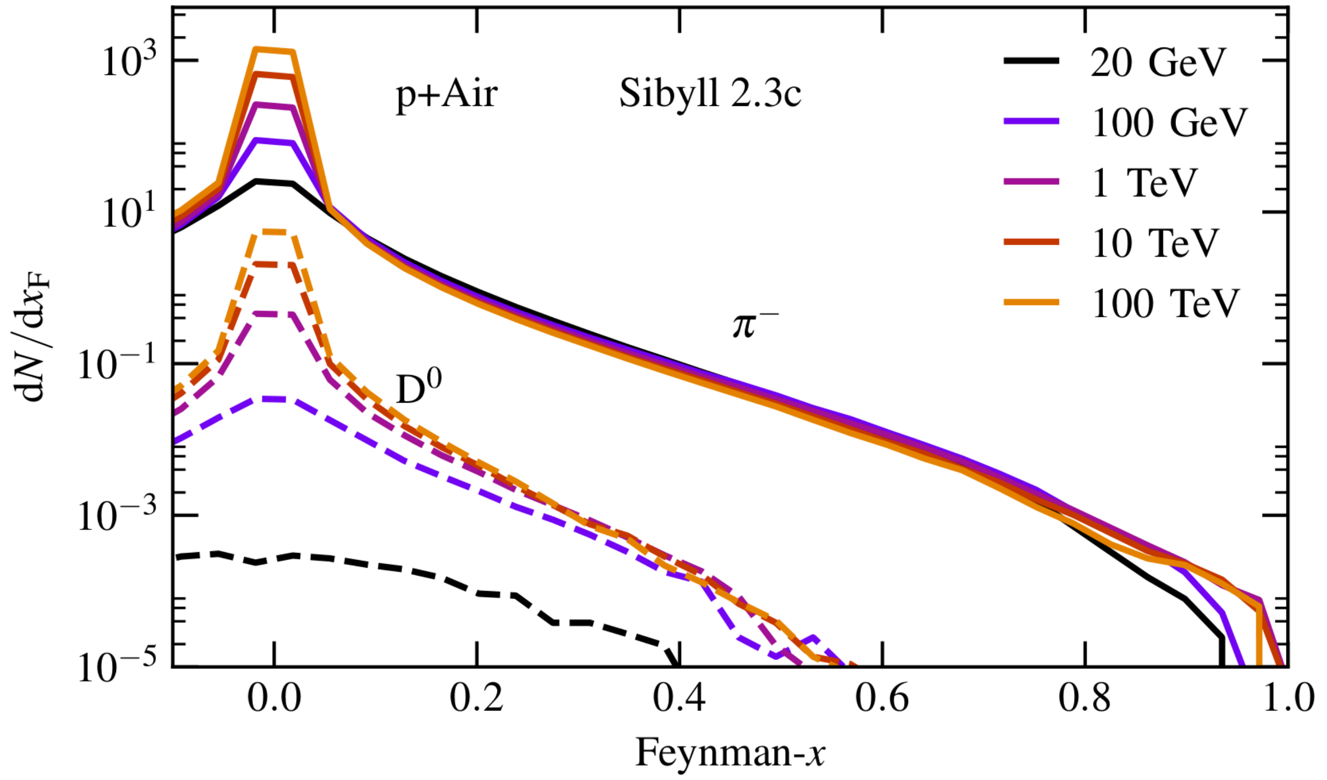
Leading particle effect



Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

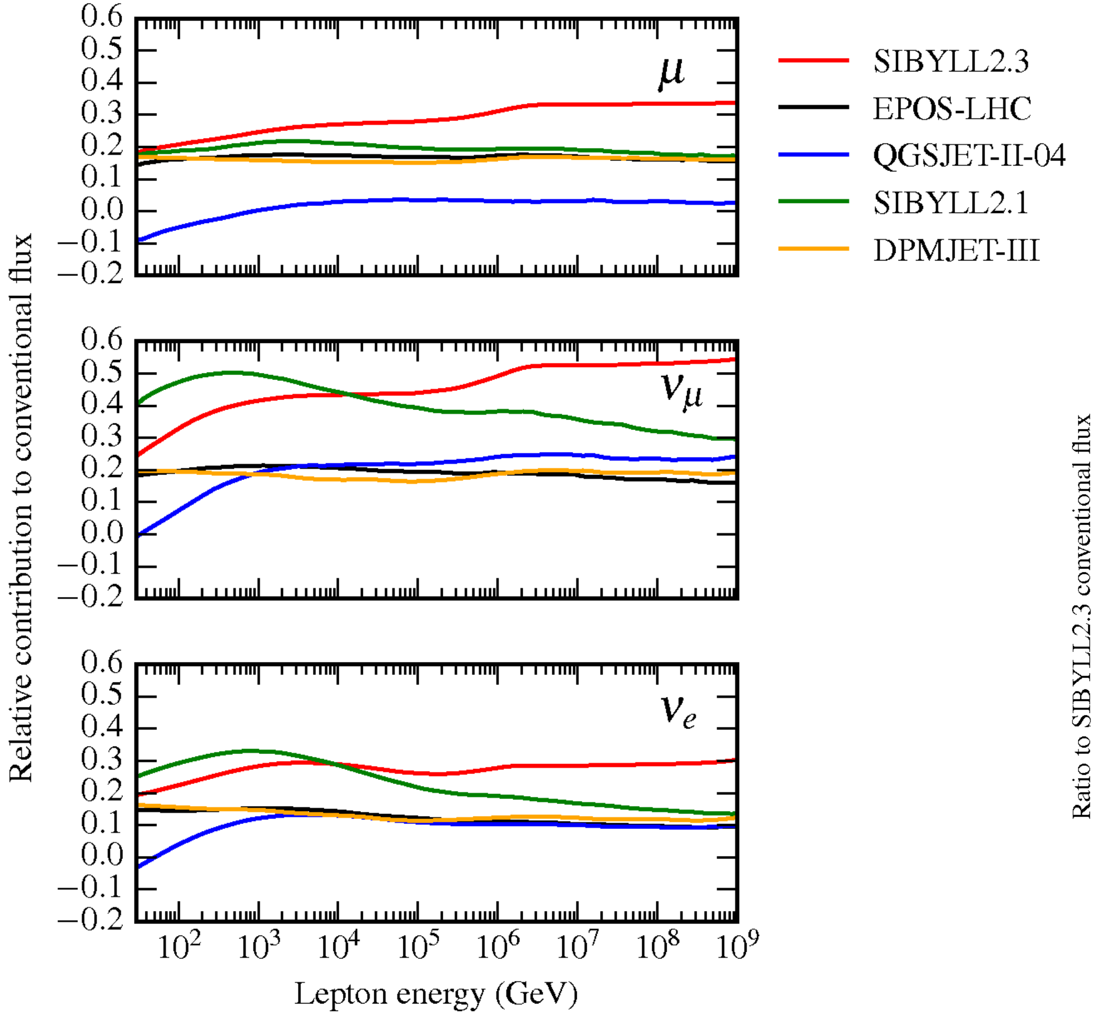
Main changes in SIBYLL 2.3c are related to scaling and leading Kaons





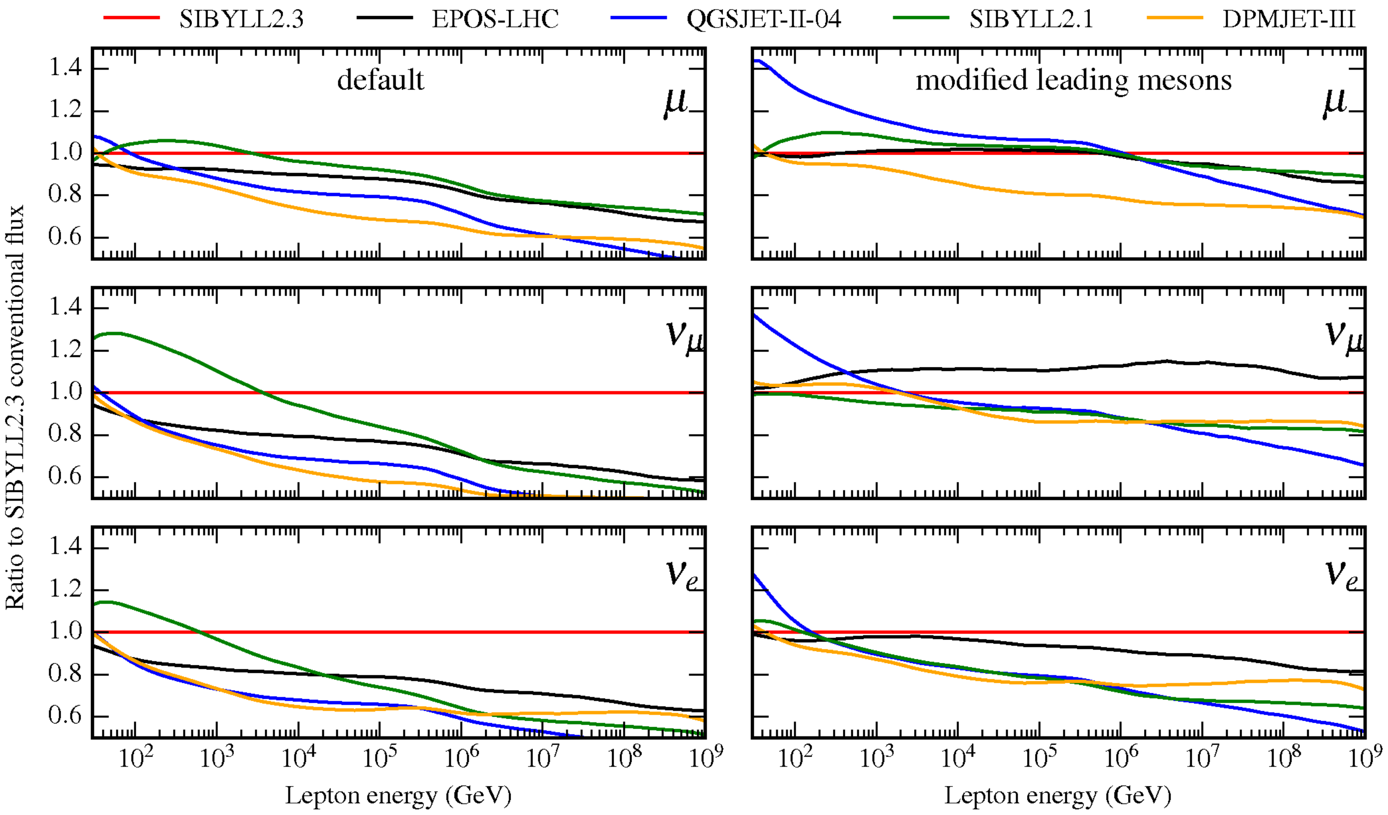
- Problems in SIBYLL 2.3 related to remnant excitation model
- No changes to charm in 2.3c
- Small changes for air-shower physics

Contribution of the leading particle effect



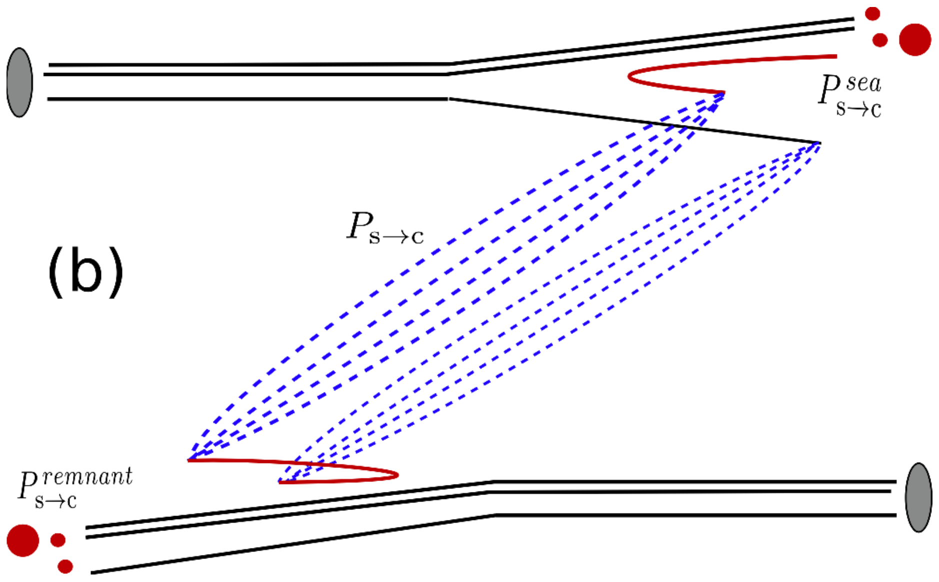
Larger effect in SIBYLL compared to other models

Modeling of leading particle effect contributes to large uncertainties

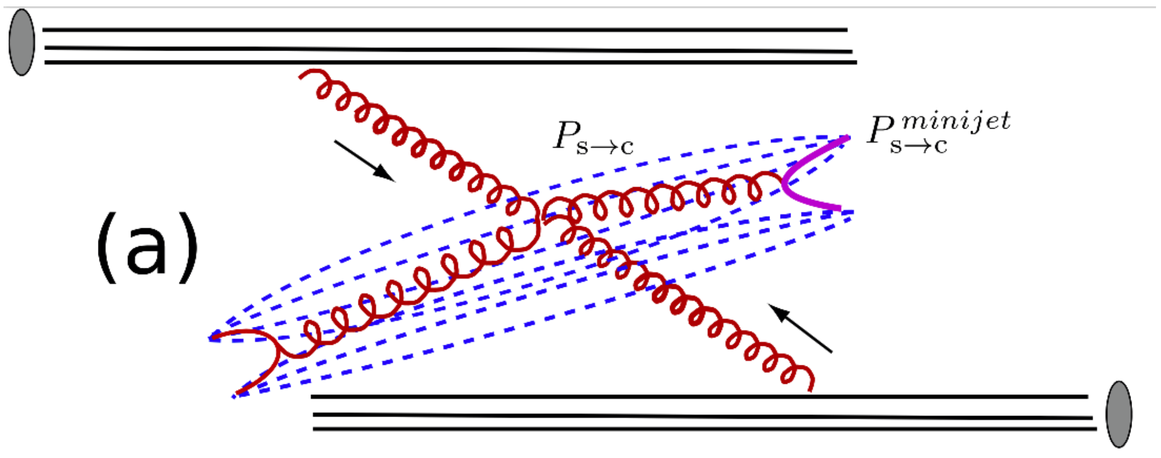


Charm in SIBYLL

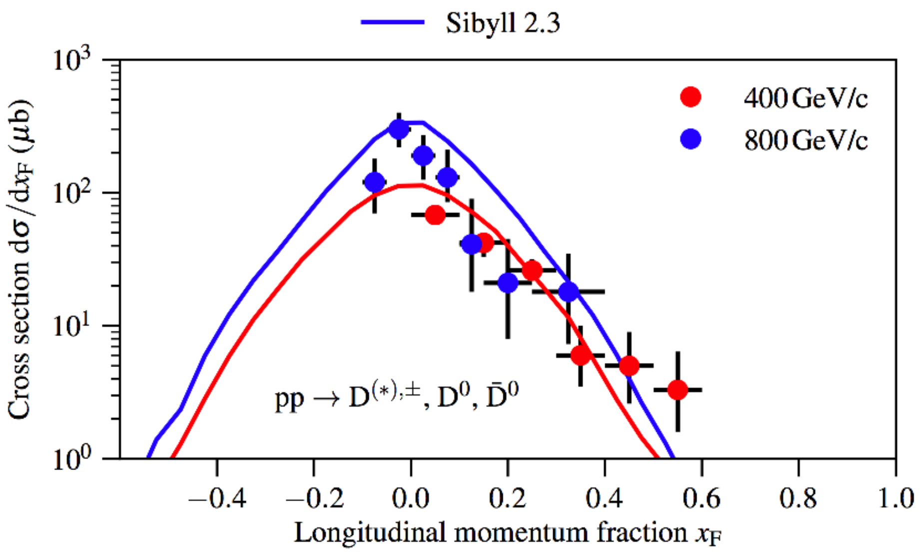
“non-perturbative/leading” charm

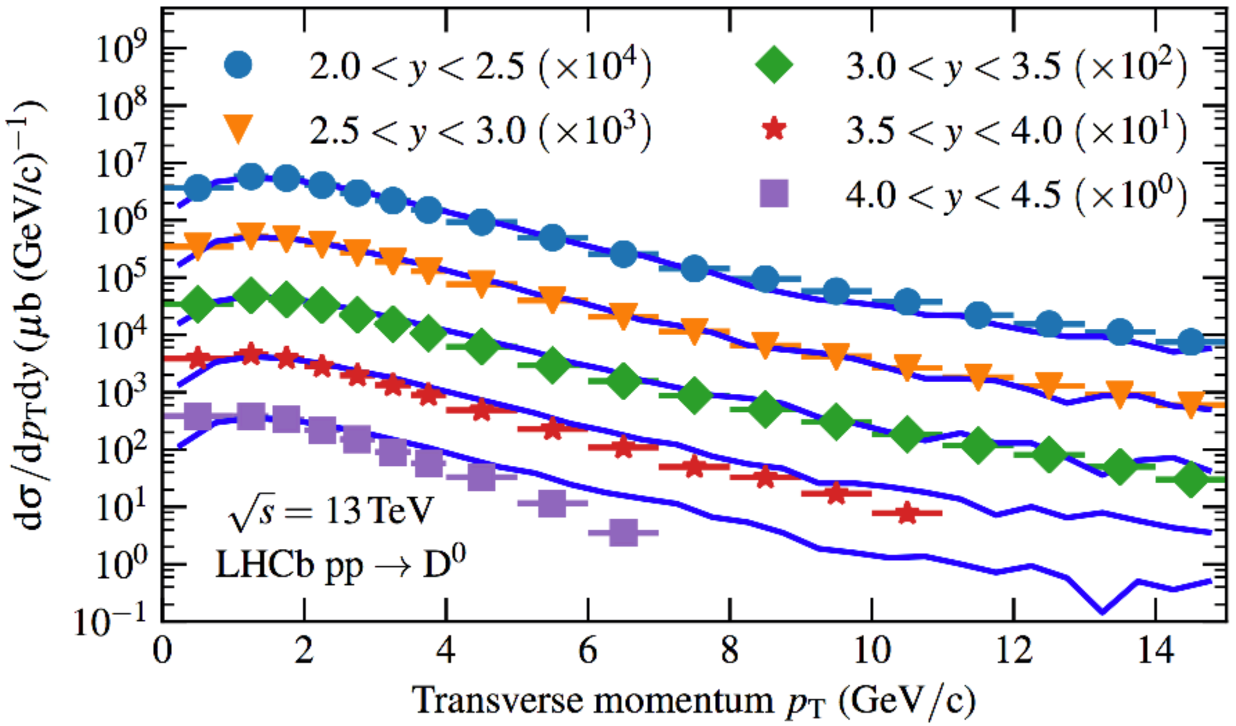


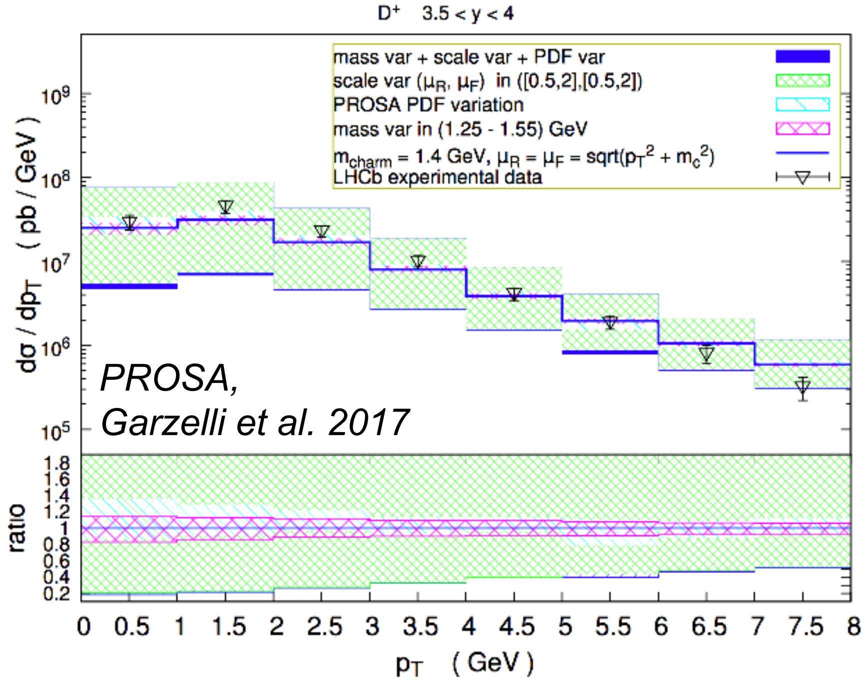
“pQCD/minijet” charm



Charm in SIBYLL

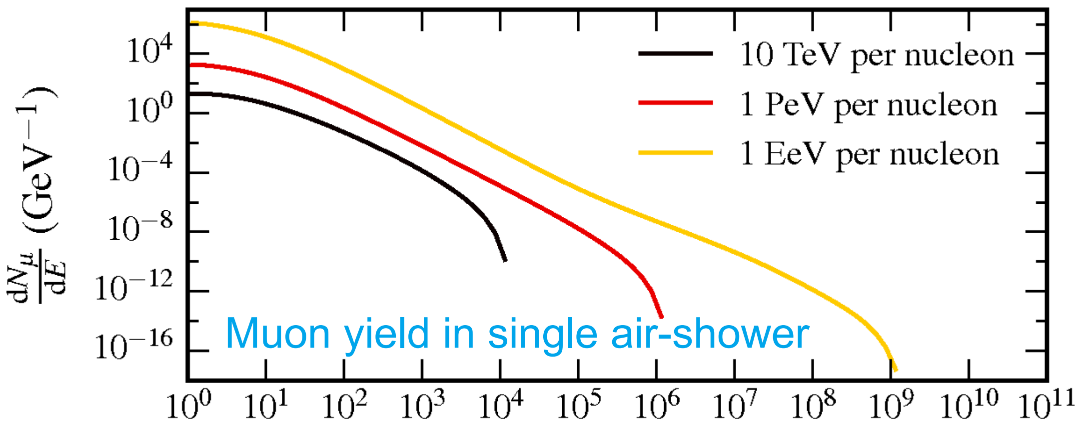


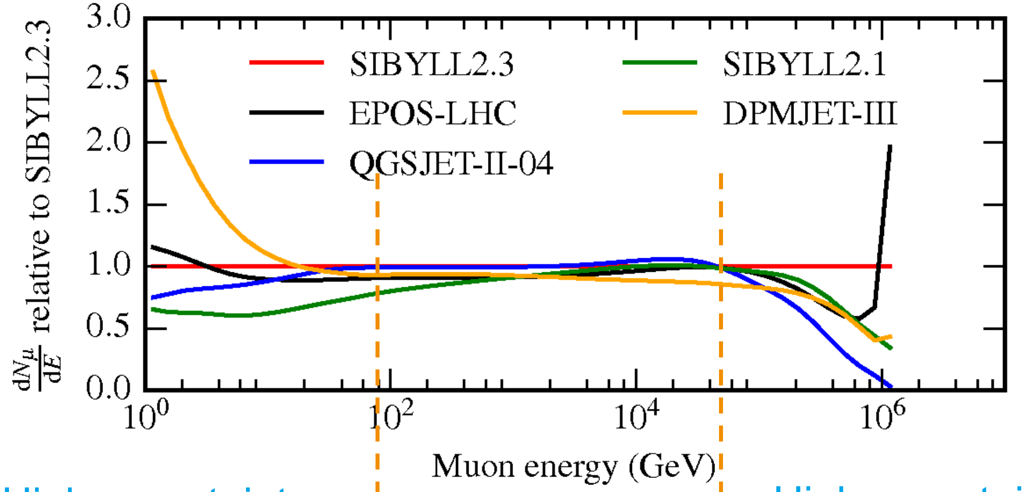




PROSA,
Garzelli et al. 2017

Large uncertainties among models

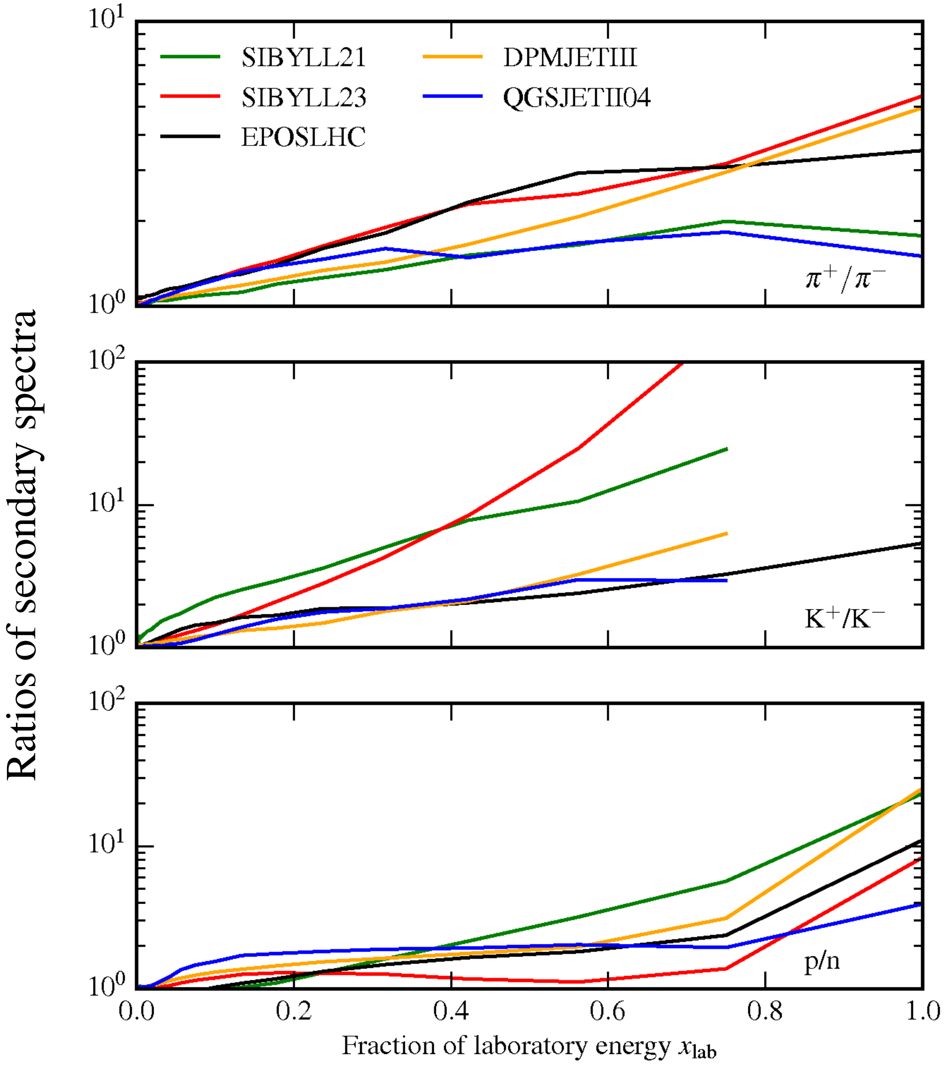




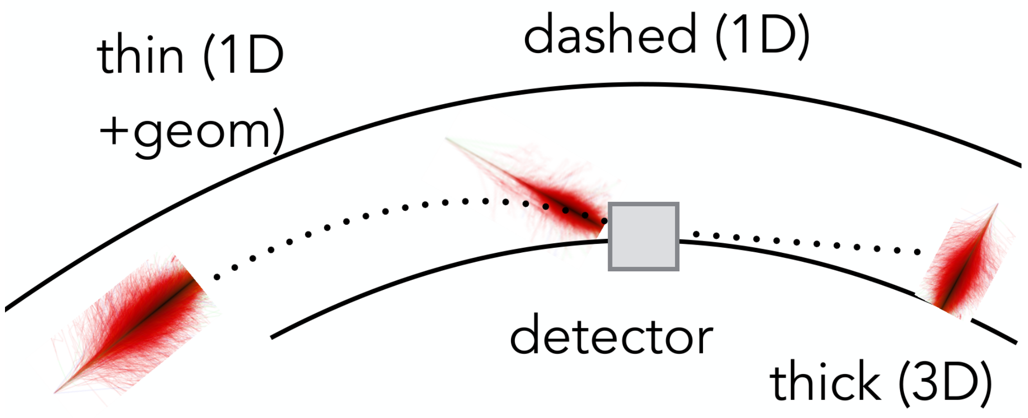
High uncertainty for air-showers

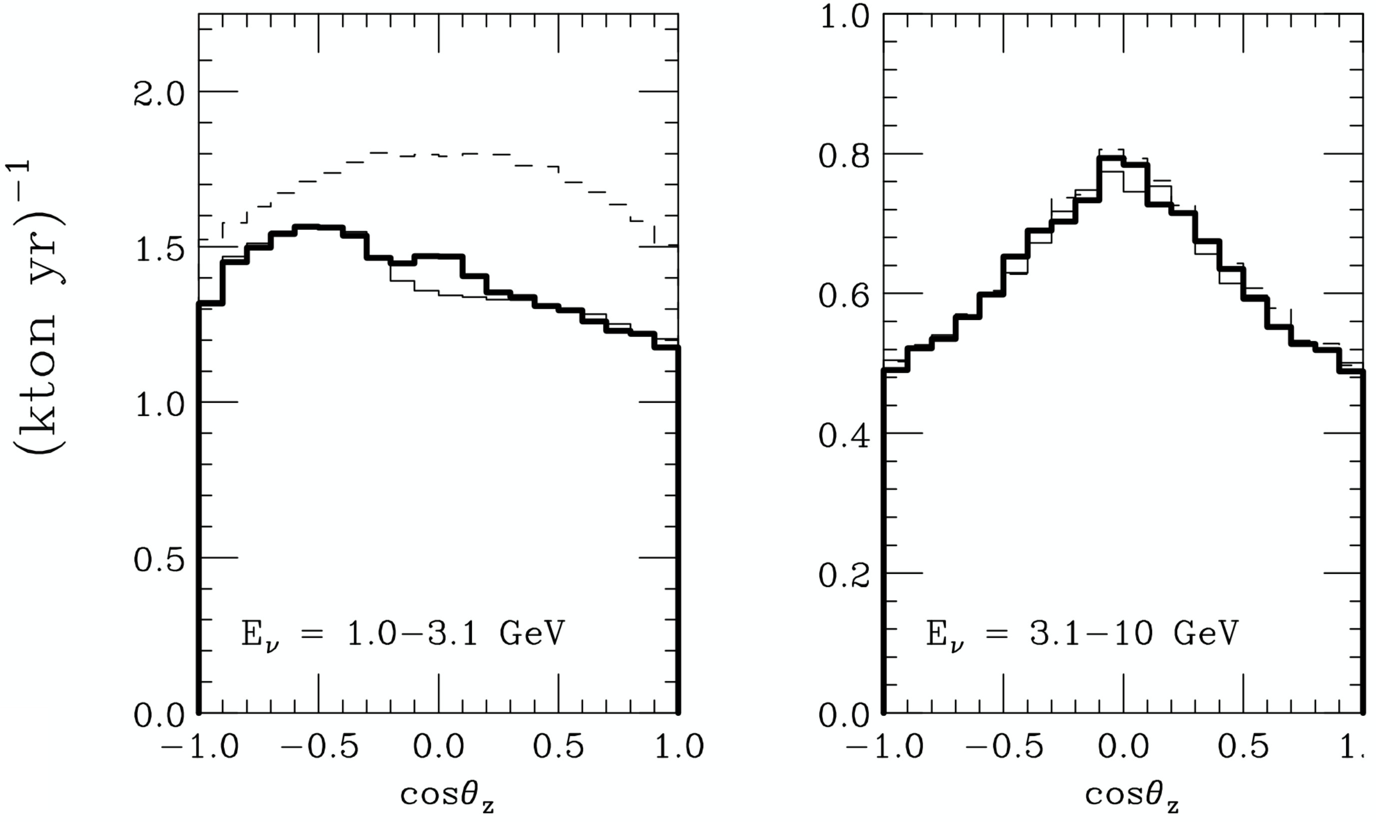
Scaling

High uncertainty for inclusive fluxes



A few words on 3D calculations





A subset of 3D calculations

[1] G. Barr, P. Lipari, S. Robbins, and T. Stanev, International Cosmic Ray Conference 3, 1411 (2003).

[2] M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, Phys. Rev. D 83, (2011).

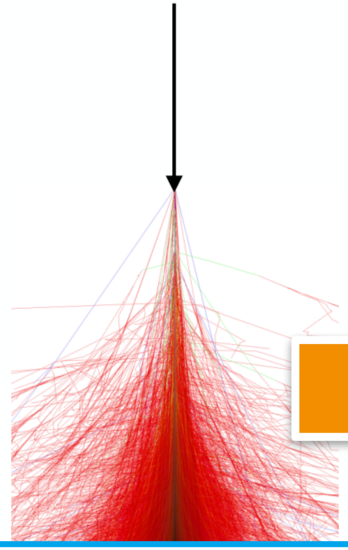
[3] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, and T. Sanuki, Phys. Rev. D 75, (2007).

[4] [1] G. Battistoni, A. Ferrari, P. Lipari, T. Montaruli, P. R. Sala, and T. Rancati, Astroparticle Physics ***12****, 315 (1999).*

[5] J. Wentz, I. M. Brancus, A. Bercuci, D. Heck, J. Oehlschläger, H. Rebel, and B. Vulpescu, Phys. Rev. D 67, 073020 (2003).

Classical solutions

1D MC calculation



For various "inputs"

primary spectrum,
zenith angle,
composition

Very slow

simulate "average"
air-shower

$$\Phi_\mu(E_\mu, \theta) = \sum_p \sum_{E_i} w_p(E_i) \times \mathcal{Y}_{p\to\mu}(E_\mu, E_i, \theta)$$

nuclei/
composition

primary spectrum

from CORSIKA

$$w_p(E_i) = \frac{1}{N_p(E_i)} \int_{E_i}^{E_{i+1}} \Phi_p(E')dE', \qquad N_p(E_i) = \mathrm{NSHOW}$$

of particles in virtual
detector

M. Honda et al. 1995, Agrawal et al. 1995, Fedynitch et al. 2012

Semi-analytical

T. K. Gaisser, R. Engel and E. Resconi,
Cosmic Rays and Particle Physics, 2nd edition

$$\Phi_\nu(E) = \frac{\phi_N(E)}{1 - Z_{NN}} \left(\frac{\mathcal{A}_{\pi\nu}}{1 + \mathcal{B}_{\pi\nu} E \cos\theta/\varepsilon_\pi} + \frac{\mathcal{A}_{K\nu}}{1 + \mathcal{B}_{K\nu} E \cos\theta/\varepsilon_K} \right)$$

- 3 – 6
- De-co

Limited detail and precision

- Numerous assumptions about spectral shape, atmospheric model, etc.
- Only asymptotical low- and high-energy solutions

DESY

MCEq: Matrix Cascade Equations

$$\frac{\mathrm{d}\Phi^h_{E_i}}{\mathrm{d}X} = -\frac{\Phi^h_{E_i}}{\lambda^h_{\mathrm{int},E_i}} - \frac{\Phi^h_{E_i}}{\lambda^h_{\mathrm{dec},E_i}(X)} + \sum_{E_k \geq E_i}^{E_N} \sum_k \frac{c_{k(E_k)\to h(E_i)}}{\lambda^k_{\mathrm{int},E_k}} \Phi^k_{E_k} \cdot \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} + \sum_{E_k \geq E_i}^{E_N} \sum_k \frac{d_{k(E_k)\to h(E_i)}}{\lambda^k_{\mathrm{dec},E_k}(X)} \Phi^k_{E_k} \cdot \frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X)}$$

Matrix-form

$$\frac{\mathrm{d}}{\mathrm{d}X}\boldsymbol{\phi} = \left[(-\mathbf{1}+\boldsymbol{C})\boldsymbol{\Lambda}_{int} + \frac{1}{\rho(X)}(-\mathbf{1}+\boldsymbol{D})\boldsymbol{\Lambda}_{dec}\right]\boldsymbol{\phi}.$$

geometry & atmosphere

flux vector

$$\vec{\phi} = \begin{pmatrix} \phi_p(E_0) \\ \phi_p(E_1) \\ \dots \\ \phi_p(E_N) \\ \phi_n(E_0) \\ \dots \\ \phi_n(E_N) \\ \phi_{\pi}^{+}(E_0) \\ \dots \\ \phi_{\bar{\nu}_e}(E_N) \end{pmatrix}$$

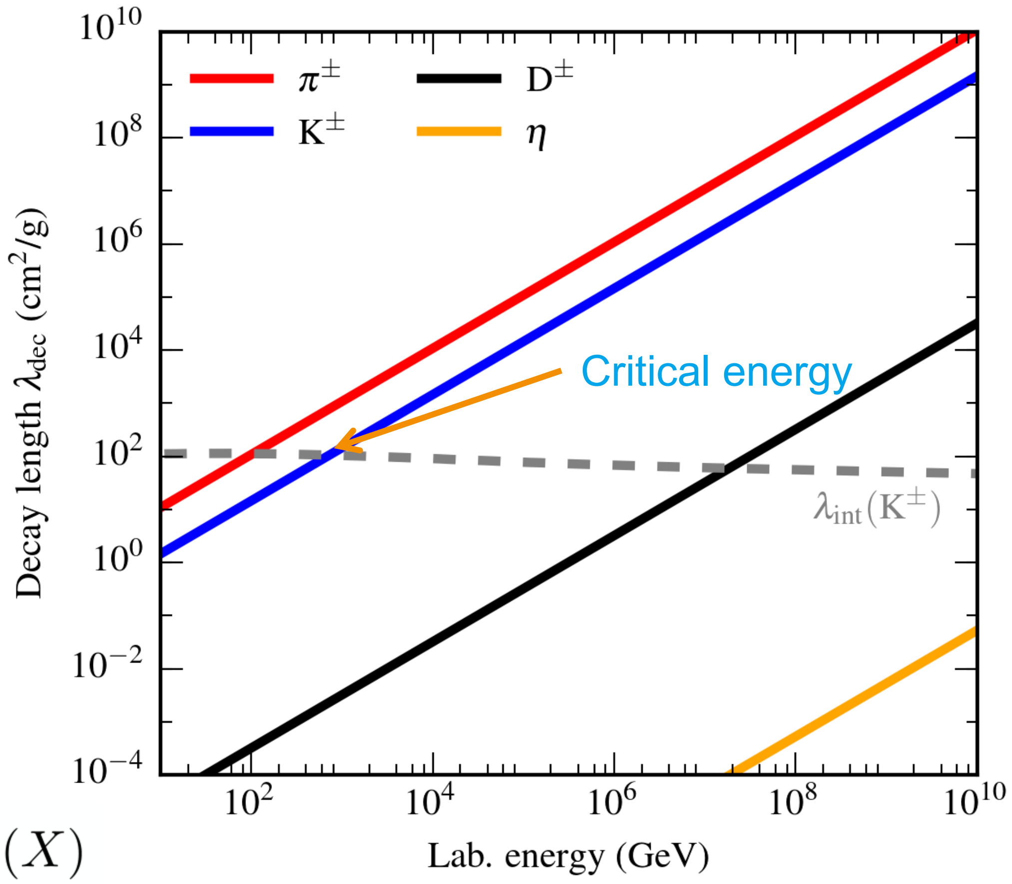
A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor
PoS ICRC 2015, 1129 (2015), EPJ Web Conf. 99, 08001 (2015)
and EPJ Web Conf. 116, 11010 (2016). Main paper in prep.

Competition between decay and interactions

- Above critical energy, probability for interaction is higher than decay probability
- Flux from one particular hadron species gets attenuated

particle	E_{crit} [GeV]
$\mu^{\pm}$	1.0
$\pi^{\pm}$	115
K_L^0	205
$K^{\pm}$	850
K_S^0	1.2E+05
$D^{\pm}$	4.3E+07

$$\lambda_{dec,h}(E,X) = \frac{c\tau_h E \rho_{Air}(X)}{m_h c^2} = \frac{EX\cos\theta}{E_{crit,h}}$$



Hadrons in MCEq

Leptons

$\mu^+,\ \mu^-,\ \tau^+,\ \tau^-,\ \nu_e,\ \nu_\mu,\ \nu_\tau,\ \bar{\nu}_e,\ \bar{\nu}_\mu,\ \bar{\nu}_\tau$

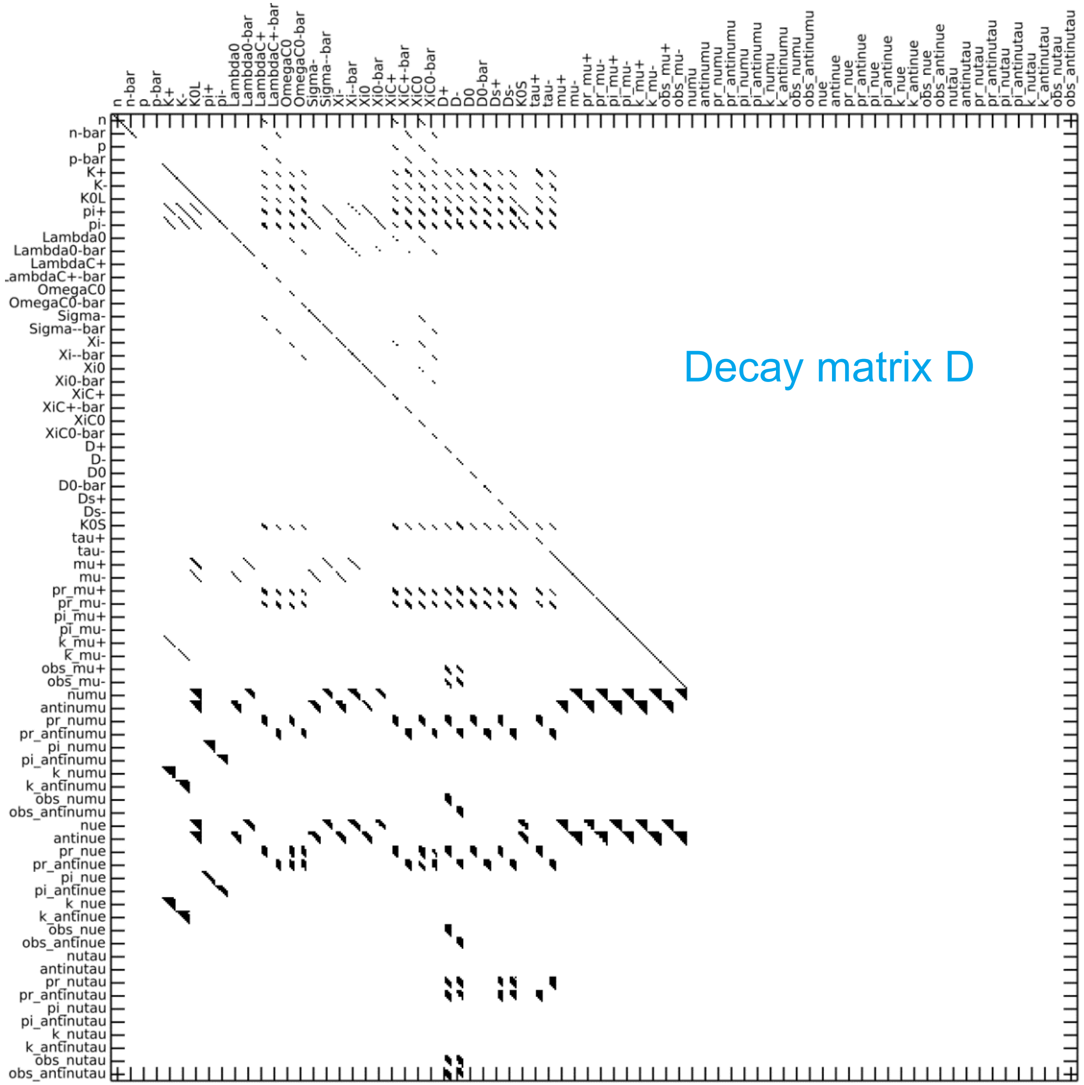
Mesons

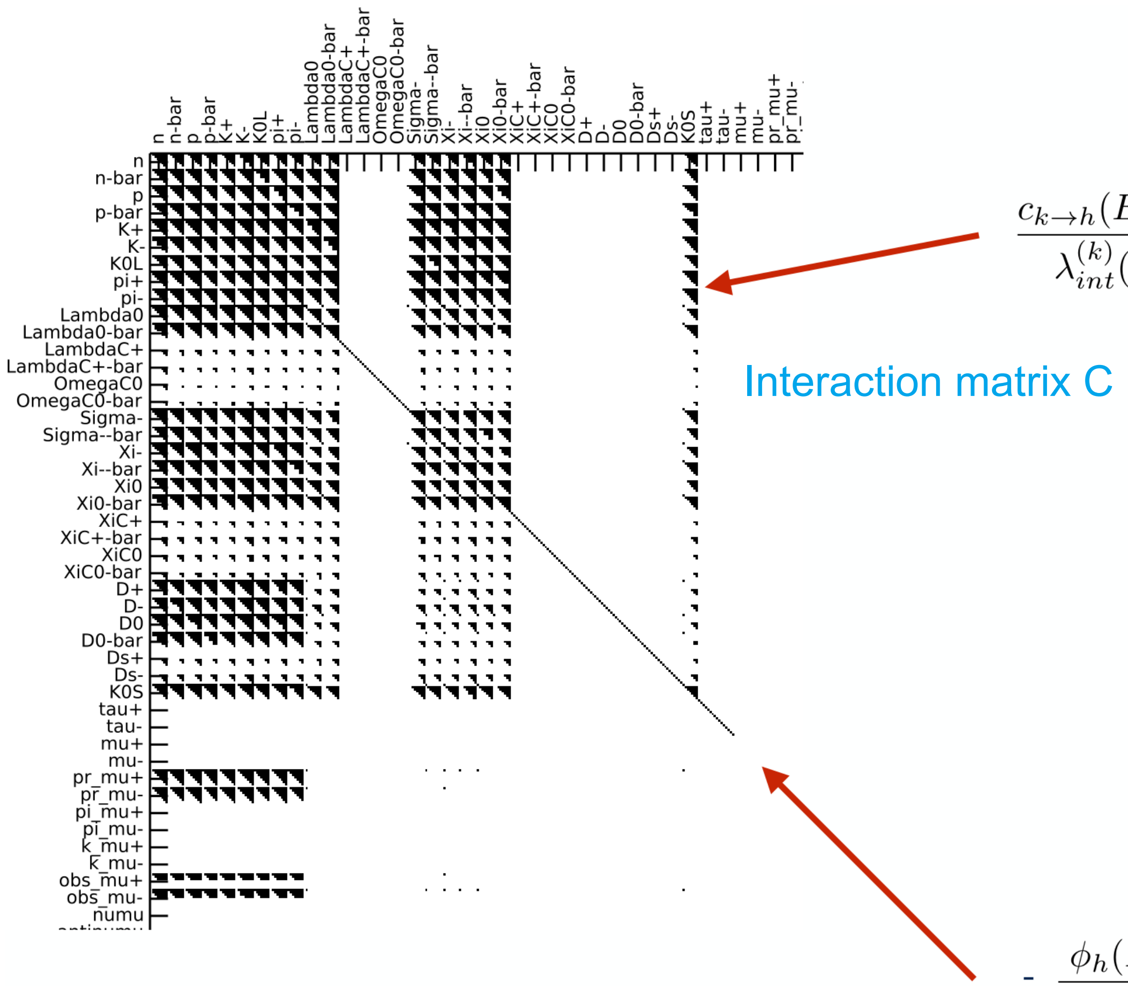
$K^+,\ K^-,\ K^0_L,\ K^0_S,\ \pi^+,\ \pi^-,\ D^+,\ D^-,\ D^0,\ \bar{D}^0,\ D^+_s,\ D^-_s,\ K^{*+},\ K^{*-},$
$K^{*0},\ \bar{K}^{*0},\ D^{*+},\ D^{*-},\ D^{*0},\ \bar{D}^{*0},\ \eta,\ \eta^*,\ \eta_C,\ J/\Psi,\ \omega,\ \phi,\ \pi^0,\ \rho^+,\ \rho^-,\ \rho^0$

Baryons

$p,\ \bar{p},\ n,\ \bar{n},\ \Delta^+,\ \Delta^{++},\ \bar{\Delta}^{++},\ \bar{\Delta}^+,\ \Delta-,\ \bar{\Delta}^+,\ \Delta^0,\ \bar{\Delta}^0,\ \Lambda^0,\ \bar{\Lambda}^0,\ \Omega^-,\ \bar{\Omega}^+,$
$\Sigma^{*+},\ \bar{\Sigma}^{*-},\ \Sigma^{*-},\ \bar{\Sigma}^{*+},\ \Sigma^{*0},\ \bar{\Sigma}^{*0},\ \Sigma^+,\ \bar{\Sigma}^-,\ \Sigma^0,\ \bar{\Sigma}^0,\ \Lambda^+_C,\ \bar{\Lambda}^-_C,\ \Omega^0_C,\ \bar{\Omega}^0_C,\ \Sigma^-,$
$\bar{\Sigma}^+,\ \Xi^-,\ \bar{\Xi}^+,\ \Xi^0,\ \bar{\Xi}^0,\ \Xi^+_C,\ \bar{\Xi}^+_C,\ \Xi^0_C,\ \bar{\Xi}^0_C,\ \Sigma^{*+}_C,\ \Sigma^{*++}_C,\ \bar{\Sigma}^{*--}_C,\ \bar{\Sigma}^{*-}_C,\ \Sigma^{*0}_C,$
$\bar{\Sigma}^{*0}_C,\ \Sigma^+_C,\ \Sigma^{++}_C,\ \bar{\Sigma}^{--}_C,\ \bar{\Sigma}^-_C,\ \Sigma^0_C,\ \bar{\Sigma}^0_C,\ \Xi^{*-},\ \bar{\Xi}^{*+},\ \Xi^{*0},\ \bar{\Xi}^{*0}$

Matrix forms



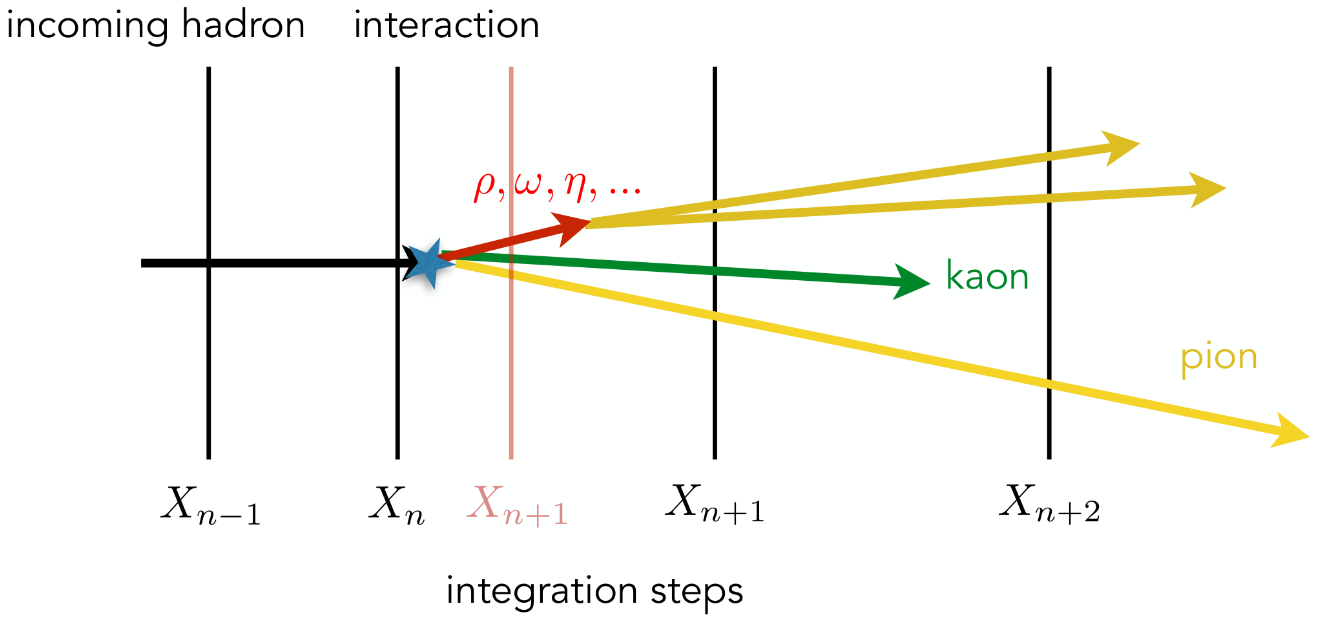


$$\frac{c_{k\to h}(E_i, E_k)}{\lambda_{int}^{(k)}(E_k)}$$

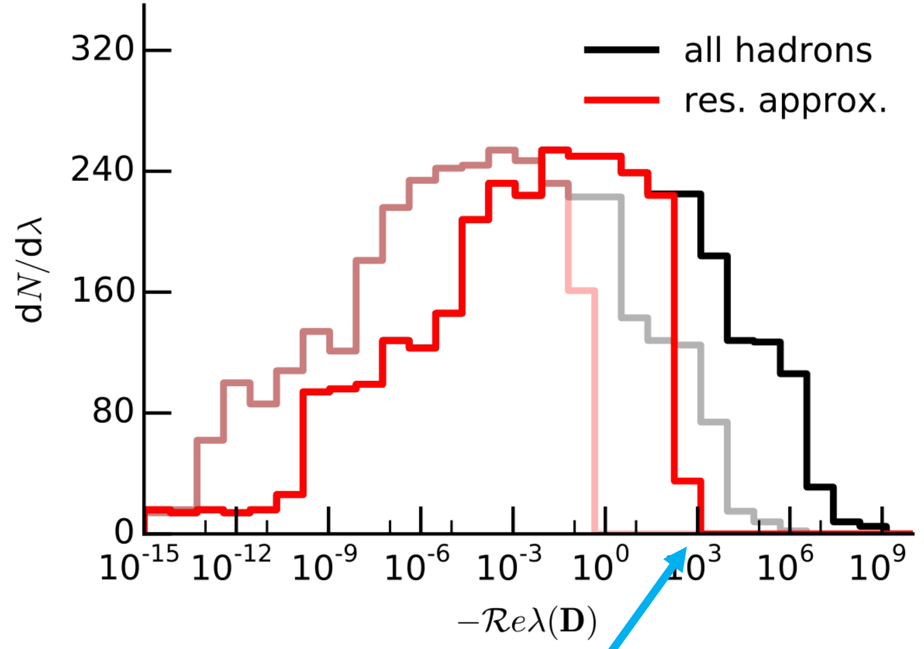
$$-\frac{\phi_h(E_i)}{\lambda_{int}^{(h)}(E_i)}$$

matrices are sparse → high performance

Stiffness is tricky



Eigenvalues of matrix equation



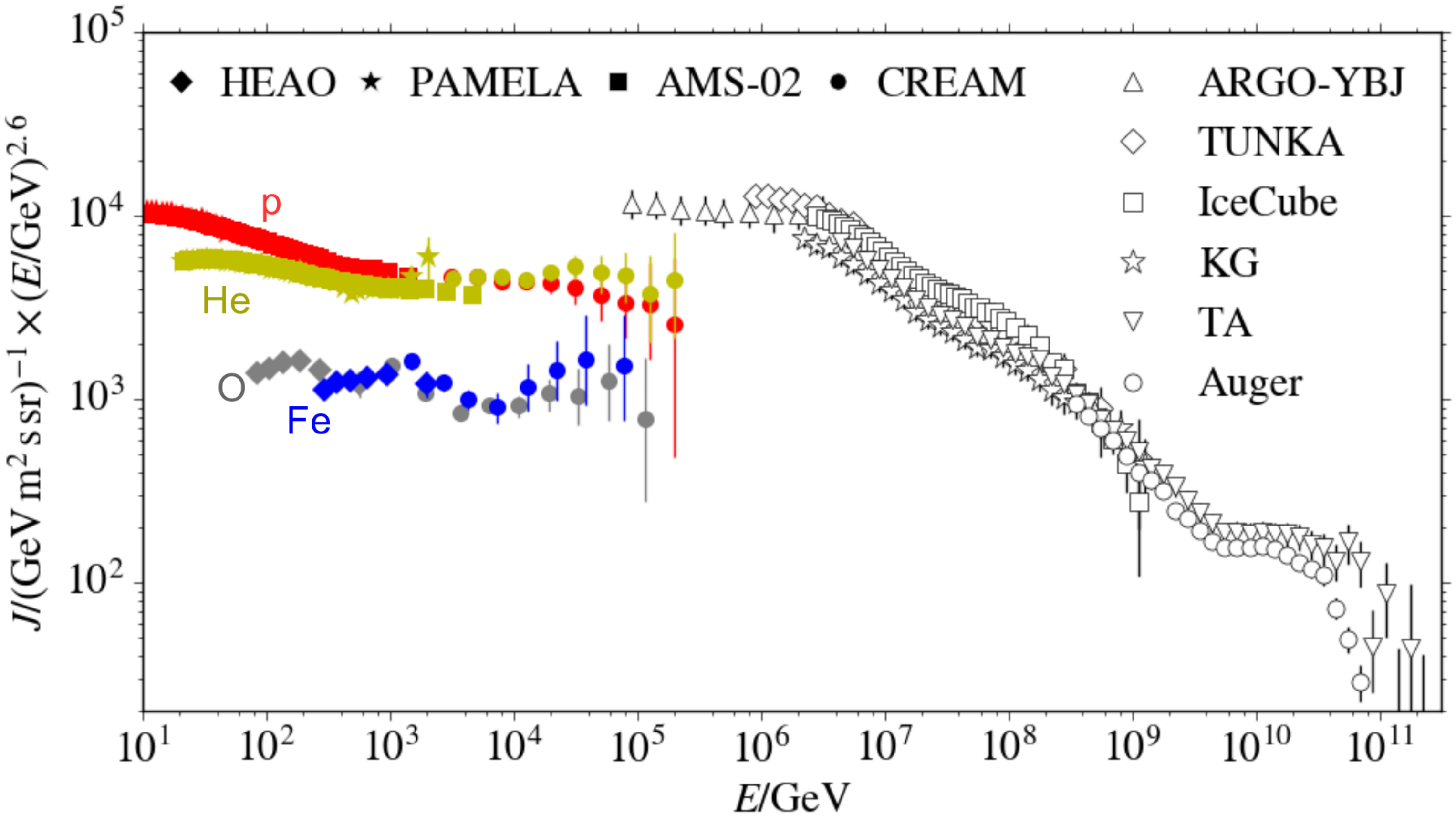
Idea: transport particles only when needed

$\lambda_{dec} < t_{mix}\lambda_{int}$	$\lambda_{dec} \geq t_{mix}\lambda_{int}$
treat as resonance	transport as particle

$$\vec{\Phi}^\omega = \left(\underbrace{\Phi^\omega_{E_0} \quad \cdots \quad \Phi^\omega_{E_i}}_{\equiv 0} \;\Big|\; \Phi^\omega_{E_{i+1}} \quad \cdots \quad \Phi^\omega_{E_N}\right)^T$$

Fastest eigenvalue controls integration step

A new take on CR flux uncertainties



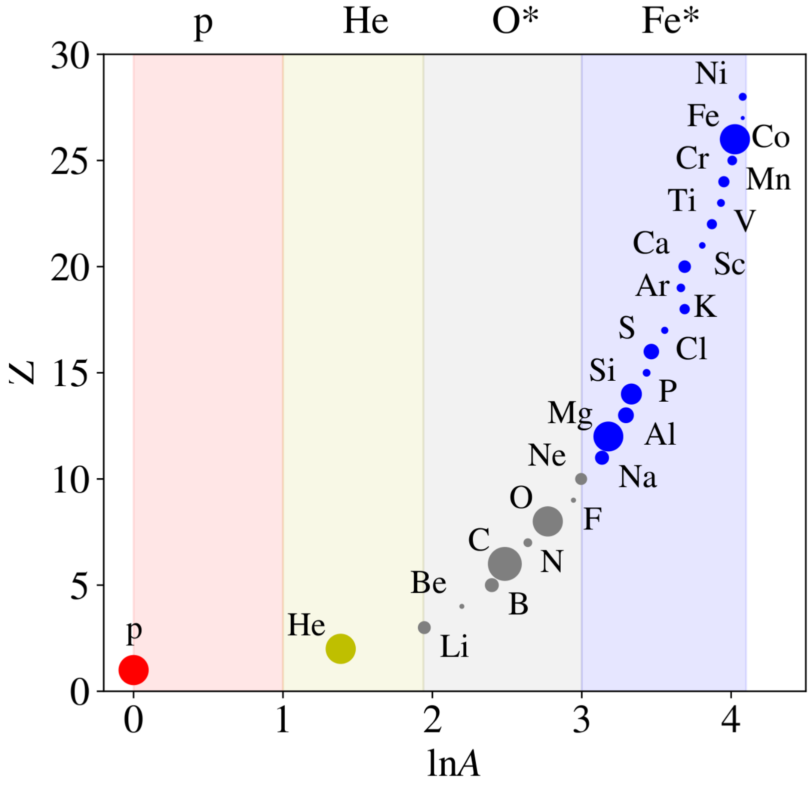
- Combine datasets from direct and indirect observations
- Use only "golden" datasets with systematic errors (incl. energy scale)
- Fit whole energy range 10 – 10^{11} GeV
- Fit composition:
  - Direct: elements
  - Indirect: mass groups

PoS(ICRC2017)533:
Hans Dembinski, AF, Ralph Engel, Tom K. Gaisser, Felix Riehn, Todor Stanev

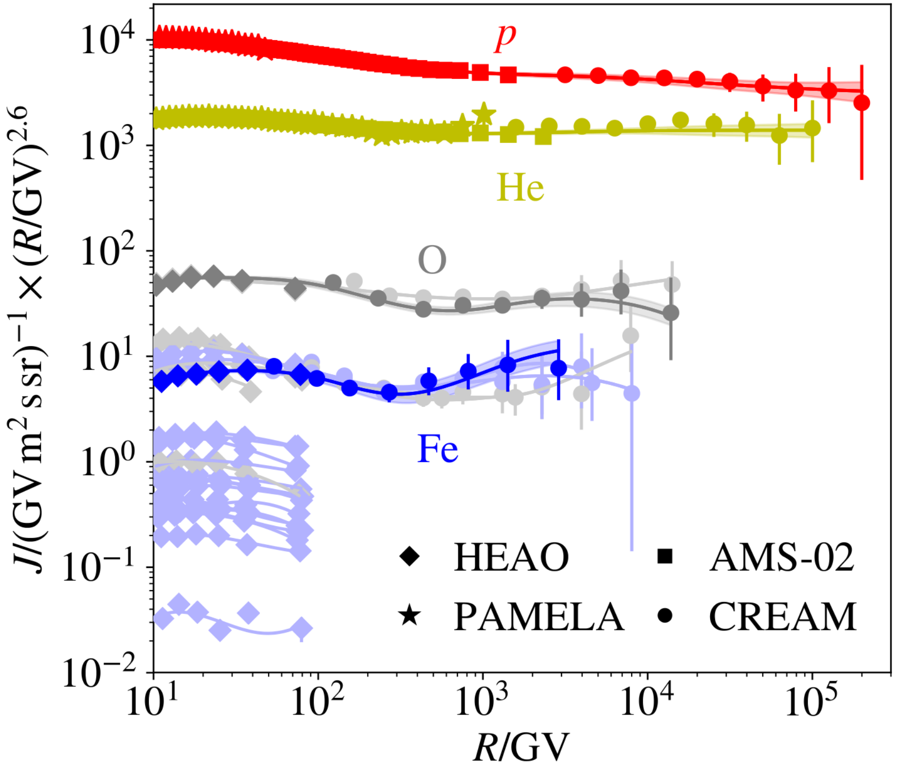
Idea: propagate uncertainties into fluxes fluxes using partial derivatives from MCEq

How to create mass groups (indirect) from element fluxes (direct)

Mass group ↔ Element

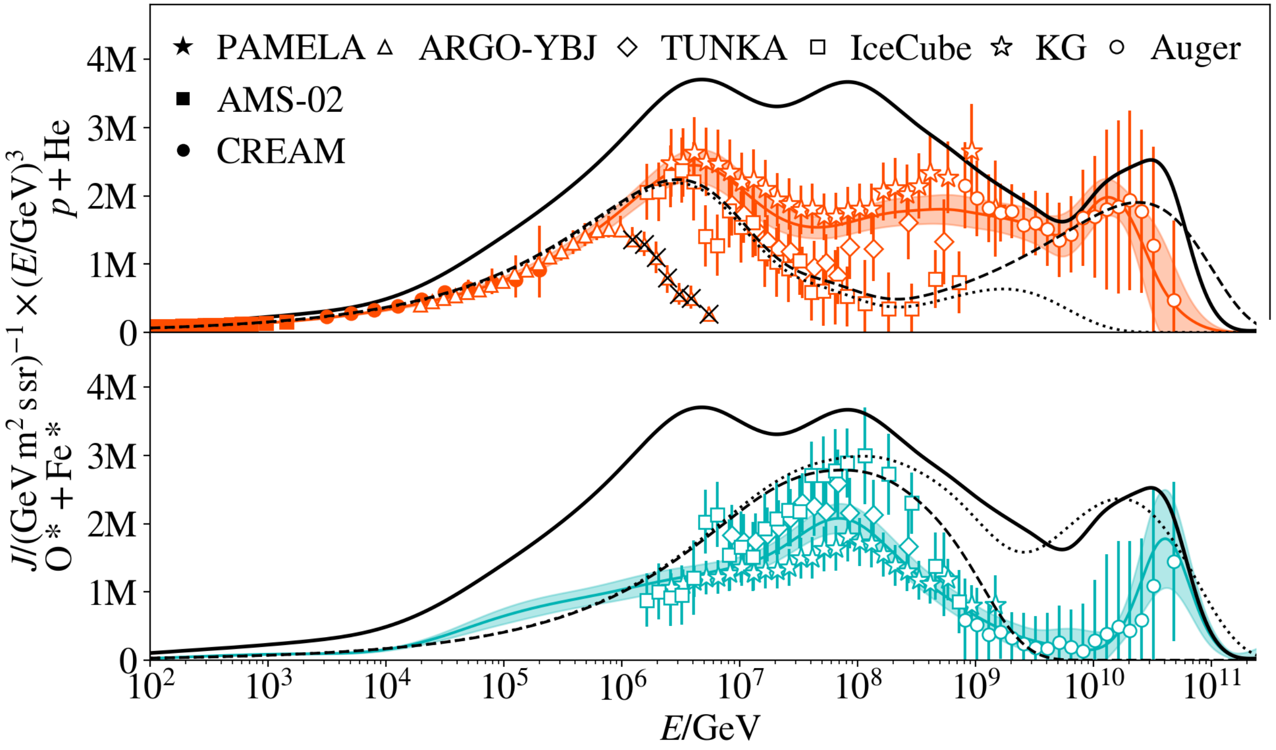


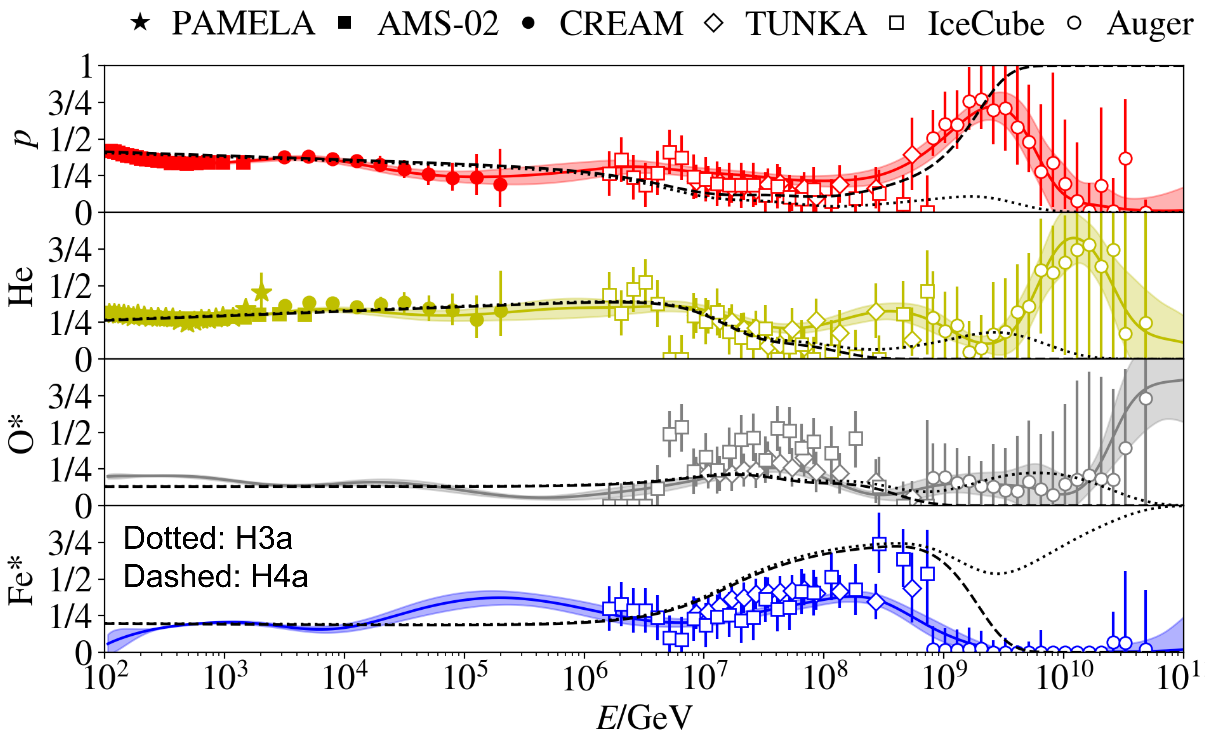
Fit of direct observations



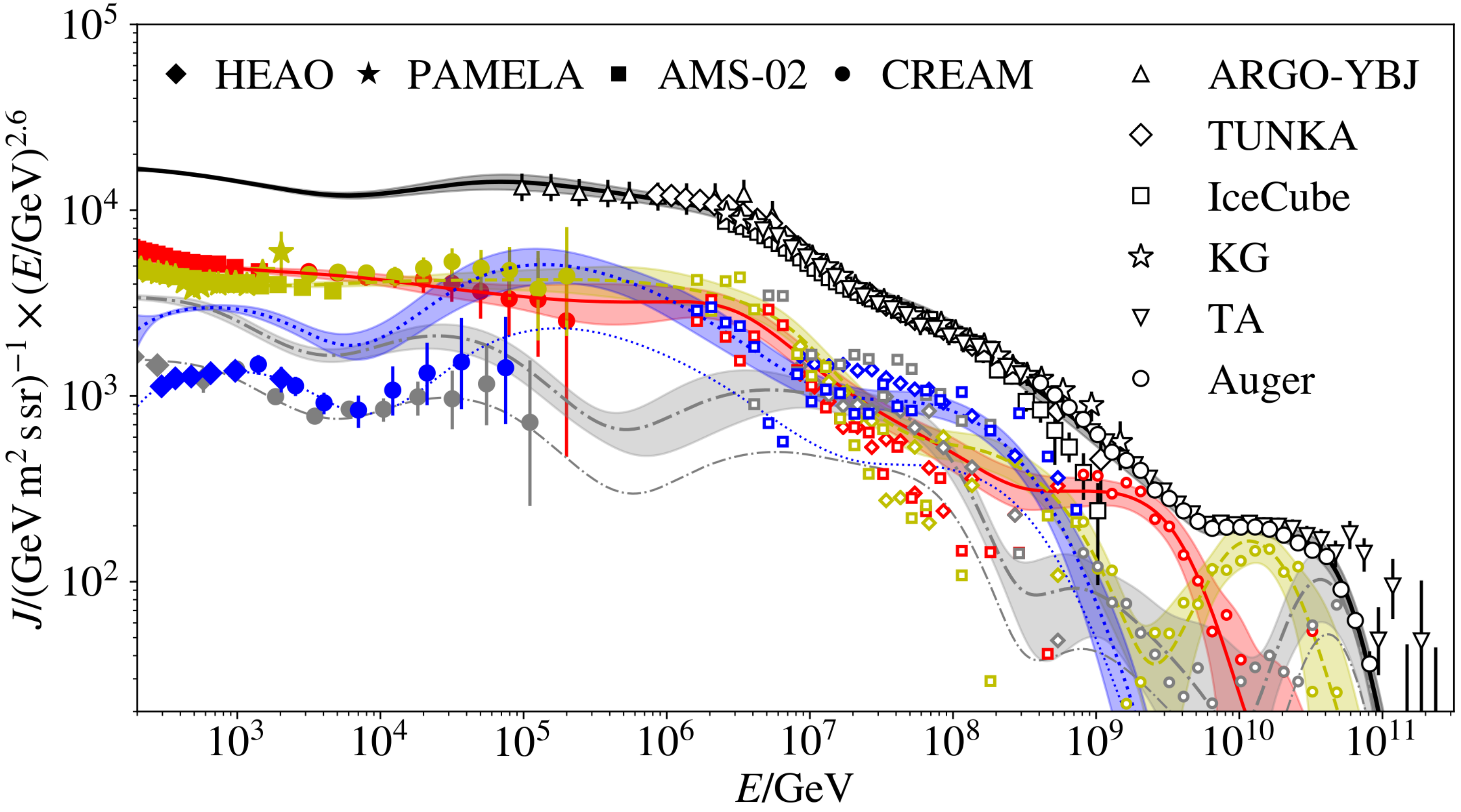
- Ratio dN/dR roughly equal for neighboring elements of a mass group
  - The only assumption (at all energies)
- Fit 4 mass groups with distinct sets of B-splines

Reproduction of data from air shower based detectors





GSF: Global Spline Fit



- Data-driven representation of the cosmic ray flux
- Full covariance matrix for all parameters
- Serves as input for flux calculations and error propagation